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Master Thesis
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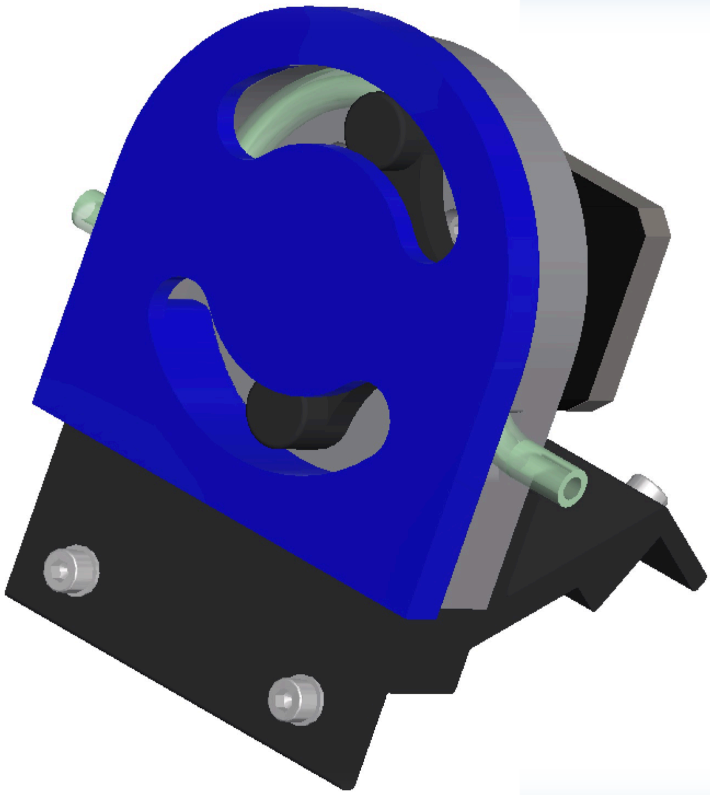
Conception, Design and Materialization of a Pumping-Based Extrusion System for Food 3D-Printing



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Master on
Key Enabling
Technologies
4 Food and
+ Bioprocess

Executive Summary

Food products become more customized to consumer's needs – consumers want food that tastes great, looks great and, besides these characteristics, is healthy. Food 3D printing is a method of distributing food in individualized manner and it could become the right technique to satisfy previous demands. The technique of 3D printing belongs among the newest technologies in recent years. For this reason, there are still many possibilities of extending the use of this technology in various fields and one of these fields is also the food industry.

Work on this master thesis has been carried out in cooperation with the Fundació CIM - project RepRapBCN, which has developed 3D printer called BCN3D+. In this project, two variants of the end effectors – the extruder and the syringe tool - have been developed. Use of an extruder is preferred mainly due to the possibility of continuous flow of printed material, but the main disadvantages here are the problem with cleaning the end effector workplace and a high cost of manufactured components in the extruder head. Another method is to use a syringe tool. Here, the drawback of difficult cleaning of equipment is eliminated and it is possible to change quickly various materials during printing. On the other hand, there is a drawback caused by the limited volume of the syringe tool vessel. If we want to print larger products, it is often necessary to reconfigure the end effector to fill the vessel of the syringe tool repeatedly.

The aim of this master thesis is to provide the design of the system for the food printing that would eliminate the disadvantages of previous variants. Within the conceptual design and study of alternatives, an overview of existing methods of pumping has been elaborated. The main objective of this section is to provide an overview of the techniques and equipment used for pumping materials in the food industry, where it is important to observe health and safety regulations and subsequently to choose a suitable equipment and features of the device. Within the detail design section, a design of basic parameters of the pump according to the selected operating requirements has been elaborated. Therefore, with help of the modeling software, 3D model and manufacturing drawings of individual pump components were provided. It has been elaborated a feasibility study of the project. The costs associated with engineering and design costs 4 300,00 € and the cost of the product including material and manufacturing costs 37,43 €. With the help of the economic viability indicator it has been calculated that the return of the investment is 1.1 years from placing the product on the market. At the end of the project, it has been processed a real model of the equipment.

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1. Introduction

The technique of the 3D printing is any of various processes used to make a three-dimensional object. It enables small quantities of customized goods to be produced at relatively low costs, which is an important aspect distinguishing the 3D printing from other rapid prototyping technologies. The technique of 3D printing that is sometimes called additive manufacturing is a digitally controlled robotic-based construction process. This technique of the 3D printing used in the food industry is contemporary robotic construction process, which builds up complex solid forms layer by layer, applying phase transitions or chemical reactions to fuse layers together. The use of the 3D printing in the food industry is a relatively new technology, so until now only a few 3D print equipments already used in industry have been developed. Most of the equipments are still in the stage of elementary concepts or patented basic designs. The advantage of 3D printing technology is the possibility of producing a specific product that can be modified during the process itself. This reduces the cost in comparison with conventional manufacturing techniques. 3D printing is preferably used in individual production or small batch production. The range of materials that can be processed by the 3D printer is very wide. The basic material properties required are the ability to flow and also to create objects layer by layer. To select and customize the proper design of the pump as a main force equipment, it is necessary to define the properties of the substance to be pumped. In case of pumping food materials, a suitable construction material must be selected to avoid affecting the quality and taste of the pumped material. The design of the pump depends on the chemical and physical properties of pumped media. During the pumping, damage or depreciation of the pumped material should be avoided. On the other hand, in some processes, disintegration of the initial material during pumping could be desirable. Main requirements for food pumping applications are that pumps should be efficient, gentle with the product and easily cleanable.

2. RepRap Machines

The technique of the 3D printing is any of various processes used to make a three-dimensional object. It enables small quantities of customized goods to be produced at relatively low costs, which is an important aspect distinguishing the 3D printing from other rapid prototyping technologies. The second major difference between these technologies is that the 3D printers seamlessly integrate with computer assisted design software (CAD). The detailed characterizations of the 3D printing are shown in Table 1.

Table 1. Characteristics of 3D manufacturing [1]

Advantages of 3D printing in comparison to other technologies
Can economically build custom products in small quantities. Source of cost effectiveness include: - No need for costly tools, molds or punches - No scrap, milling or sanding requirements - Automated manufacturing - Use of readily available supplies - Ability to recycle waste material - Minimal inventory risk as there is no unsold finished goods inventory - Improved working capital management as goods are paid for before being manufactured
Ability to easily share designs and outsource manufacturing
Speed and ease of designing and modifying products
Important 3D printing applications
Small production run applications of 3D printing - Mass-customized products - Prototypes - Replacement parts - Medical/dental applications
Current limitations of 3D printing
- Higher costs for large production runs relative to injection molding and other technologies - Reduced choice for materials, colors and surface finishes - Lower precision relative to other technologies - Limited strength, resistance to heat and moisture, color stability

Technique of 3D printing that is sometimes called additive manufacturing is a digitally controlled robotic-based construction process, which builds up complex solid forms layer by layer. Generally, it is a product construction made by applying phase transitions or chemical reactions to fuse layers together. In the additive manufacturing processes a digital template of the desired 3D shape is produced by splitting the design shape into slices, which allows constructing the product in consecutive layers from the bottom up [2].

2.1. RepRap community project

The RepRap project started as a British initiative to develop a 3D printer that can print most of its own components. RepRap is an open-source self-replicating rapid prototyping machine that uses the fused-filament fabrication to make final product. Generally, construction of the printer consists of a thermoplastic extruder mounted on a computer-controlled Cartesian XYZ platform. The main idea of this project is that the RepRap machine has been designed to be able to print out a significant fraction of its own parts automatically and all its remaining parts have been selected to be standard components cheaply and widely available worldwide.

Dr. Adrian Bowyer, professor at the University of Bath in the United Kingdom, founded RepRap community blog in 2005 but the first printer (Fig. 1) that could produce more than half their own part was made up in 2008 [3].

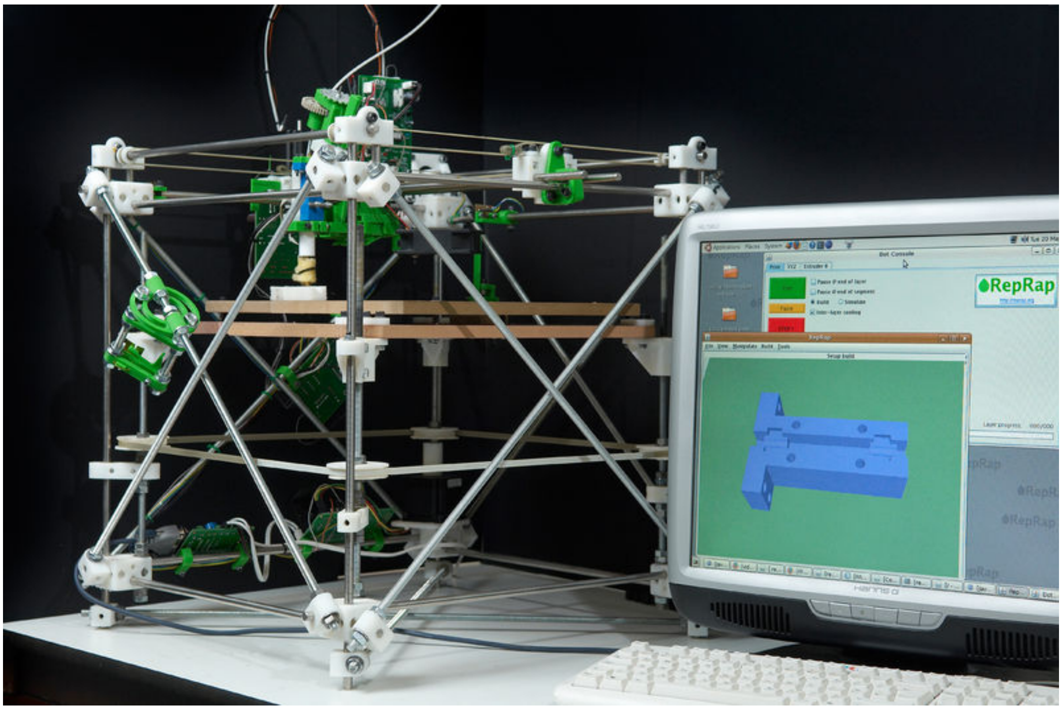

Fig. 1 RepRap version Darwin [3]

At the start of the year 2008 four RepRap machines officially existed and all of these printers have been made on commercial rapid prototyping machines. The second-generation design, called Mendel is improved version of RepRap Darwin. This type of construction is nowadays most frequently used and modified in many other structures. Figure 2 shows printers designed by Josef Průša, which are now probably the most replicable. The left part of the picture presents the Prusa Mendel printer, which was released in 2011. A newer version of the Prusa Mendel model is shown on the right. Prusa i3 is a very popular design, which led many people to create modified versions. It was estimated in 2010 that there existed about 4.500 derived printers all over the world. As the project was designed by Dr. Adrian Bowyer to encourage evolution, many variations have been created. For this open source project designers, are free to make modifications and substitutions but it is necessary to re-share their own improvements.

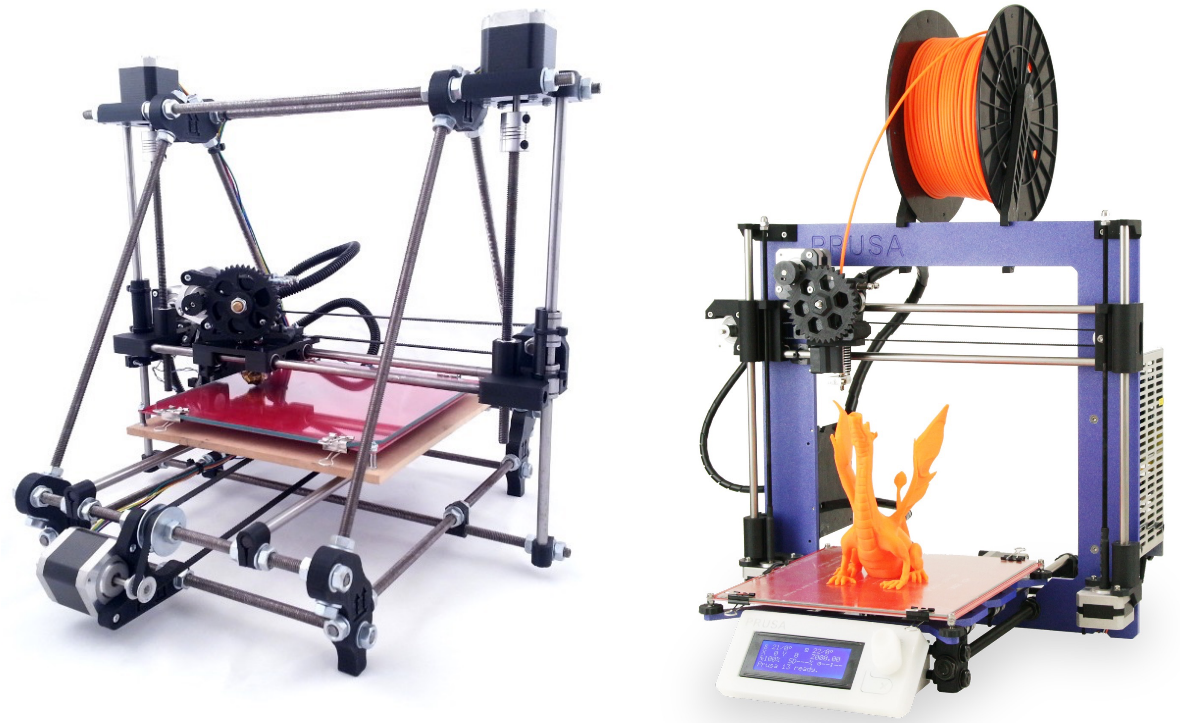

Fig. 2 Prusa Mendel and Prusa i3 RepRap 3D printers [4]

Although the aim of the project is to be able to autonomously construct as many own mechanical components as possible, several components such as sensors or stepper motors are currently non-replicable using the 3D printing technology and therefore have to be produced independently of the RepRap self-replicating process. The goal of the RepRap community project is to approach 100 % replication of printer's components in the future.

2.2. Fundació CIM - RepRap

Fundació CIM (computer integrated manufacturing) is an entity attached to the Universitat Politècnica de Catalunya (UPC) - BarcelonaTech that has the institutional mission to transfer knowledge of engineering and technology management to companies and professionals seeking to expand the possibilities of the industry in their territory through the creation, improvement and promotion of its products and manufacturing processes. As a leading technological center, Fundació CIM - UPC also intends to bring enterprises closer to the environment of the latest innovations in the market, providing companies with facilities and resources that will allow to gain an added value in the results and final products and empower them to compete in the international market.

The CIM, created in 1989, was one of the first centers in Spain that have had equipment for 3D printing. In 2010, thanks to the scheme of European Project *Leonardo da Vinci*, the CIM could join the initiative and started making low cost RepRap 3D printers within the frames of an internal project called RepRapBCN. From the first moment, RepRapBCN was trying to use technology and knowledge generated in recent years and spread them within the whole foundation. At first its project worked with the type of printers designed by Josef Průša and called Prusa Mendel i2 (Fig. 2). However, RepRapBCN have been growing as high in production and selling as in providing workshops. These workshops are courses provided for owners of RepRapBCN printers. In January 2013, acquired knowledge allowed to introduce a new model of the BCN3D (Fig. 3a), which changed original architecture and improved every aspect of the printer - quality, print speed, level of reliability, user interface and ease of assembly. Despite the increased demand to BCN3D, it quickly highlighted the aspects that should necessarily be improve, so BCN3D+ (Fig. 3b) was designed in September 2013 with the aim to solve previous problems [6].

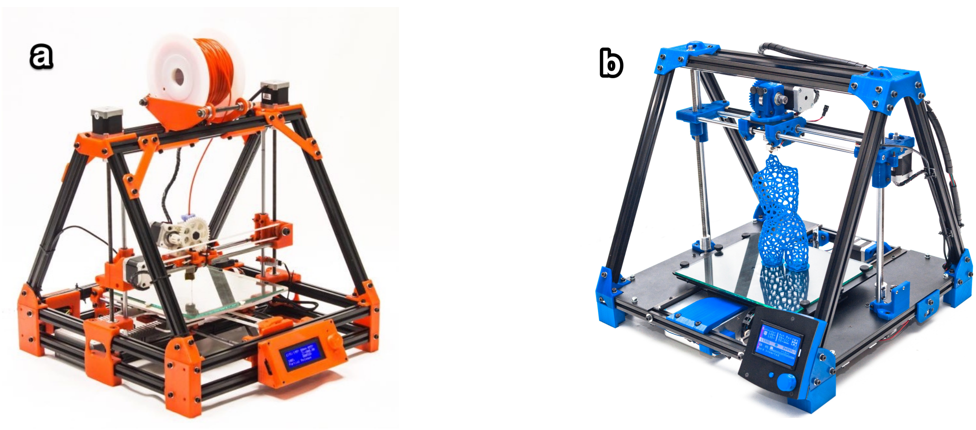

Fig. 3 Fundació CIM – RepRapBCN printers [5]

3. Definition of the project

Food products becoming more customized to consumer's needs – consumers want food that tastes great, looks great and, besides these characteristics, is healthy. Food 3D printing is a method of distributing food in individualized manner and it could become the right technique to satisfy previous demands.

3.1. Additive manufacturing in the food industry

The technique of the 3D printing used in the food industry is contemporary robotic construction process, which builds up complex solid forms layer by layer, applying phase transitions or chemical reactions to fuse layers together. For describing a new kind of food productions process, the term Food Layered Manufacture (FLM) is used that is a translation of the robotics-based additive manufacturing process into food fabrication. Additive manufacturing process is commonly known as the rapid prototyping or 3D printing which works on the principle of joining materials layer by layer to make a final 3D object.

Additive manufacturing process works with different types of materials and many types of deposition and fusion technologies. Process utilizes materials in liquid, gel, solid and powder form as well. Deposition and fusion technologies can be split into three general modes (Fig. 4). The application of the particular mode depends on the point at which the structure formation is controlled by the robotics system [2].

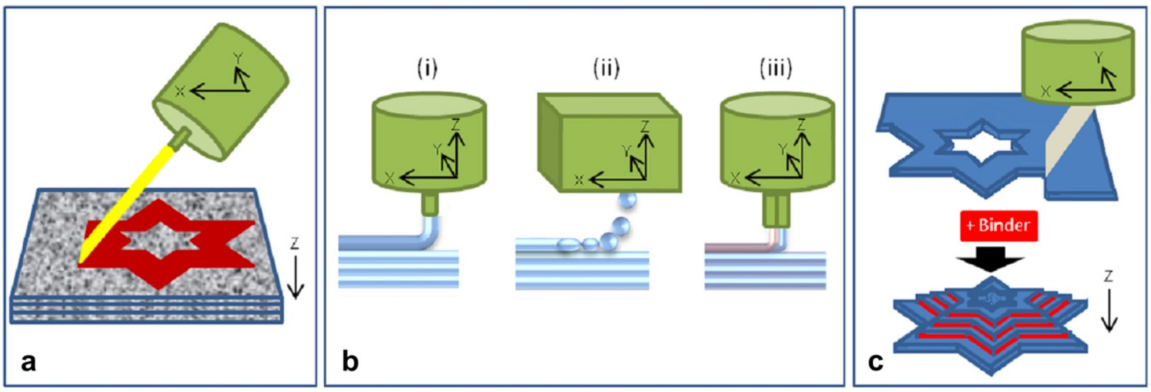

Fig. 4 Additive manufacturing technologies [2]

The first technology called Controlled Fusion (Fig. 4a) works on the principle where the heat source is directed to fuse the surface layer of a sinterable powder. After sintering the initial layer, a fresh layer of the material is applied and unfused material is removed at the end of construction. This technology is sometimes called Selective Laser Sintering where the main heat source is a laser. Examples of food structure fabricated using food layered manufacture are shown on Figure 5. Toffee structure (Fig. 5a) is formed by heat-sintering consecutive layers of sugar crystals. By the technique of heat-sintering, Nesquik shapes are also made (Fig. 5b).

The second technology is Controlled Deposition (Fig. 4b), which works on the principle of one or more extrusion printheads that are directed to deposit a continuous or interrupted stream of material layer by layer. There are many types of depositing a material: continuous stream of material (Fig. 4b, i), interrupted stream of rapidly solidified drops (Fig. 4b, ii) and co-extrusion and mixing a multiple streams (Fig. 4b, iii). Examples of food structure fabricated using a single head extrusion are chocolate forms (Fig. 5c) and cake shapes (Fig. 5d) that are made with help of twin extrusion head.

And the last additive manufacturing technology is called Controlled Cutting with Lamination (Fig. 4c), which works on the principle of shaping a base material by cutter. Then consecutive layers are assembled and fused together with a bonding layer [2].

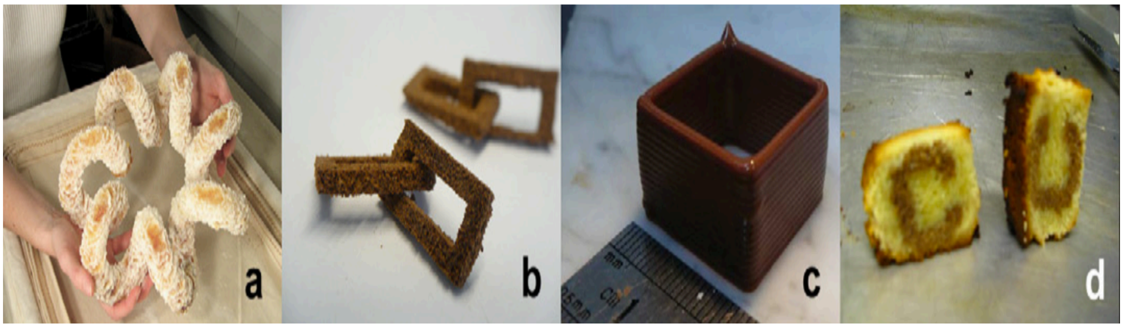

Fig. 5 Examples of food structure made by food layered manufacture [2]

The aim of the food layered manufacture technologies is to enable the consumers to create new eating experiences and to customize food according to their liking or with help of web-based design templates and recipes. But on the other hand, the technology should also provide flexibility in production in small and medium industry processes.

3.2. Existing food printing designs

The use of the 3D printing in the food industry is a relatively new technology, so until now only a few 3D print equipments already used in industry have been developed. Most of the equipments are still in the stage of elementary concepts or patented basic designs. In history, many technologies developed for general manufacturing have been transferred to the food manufacturing. This has been for instance the case of the use of the steam power, mechanical stirring, electric heating or robotic manipulation. The use of the 3D printing technology is the same case. Most of the 3D printers concepts are based on already existing designs used for the printing of the plastics materials. The function of these printers and the way how the hardware and software work together is mostly the same in all cases of these concepts. Existing 3D food printer consisted of three main blocks - computer, control box and Cartesian robot. Function of food printer works on the principle that user can interact with the machine via personal computer and a special software. The software allows interacting with the motor in control box, which in turn controls all the food printer motors. So the control box accordingly controls all movements of the Cartesian robot. Typical existing 3D food printer consisted of a three-axis Cartesian CNC machine driven by a stepper motor. There are many conceptual designs and patents in the literature that are relevant to food printing technology.

Fab@Home 3D Printer

The Fab@Home 3D printer (Fig. 6) is a three-axis Cartesian robot machine with one or two syringe pump used in the end effector head. Fab@Home Cornell University's project team tests a variety of food materials which include: frosting, chocolate, cheese or caramel and cookies.

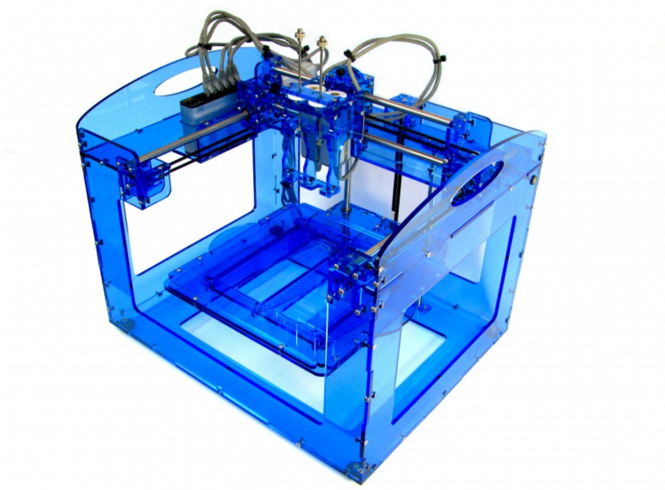

Fig. 6 Fab@Home Fabber Model II [11]

Electrolux Moléculaire concept

Electrolux Moléculaire is the 3D molecular food printer (Fig. 7) that relies on the experimental molecular cooking technology. This type of printer uses a small robotic arm, which distributes the food particles from the inner tank to the workplace. Electrolux Moléculaire also allows multiple materials to be printed [9].

Fig. 7 Electrolux Moléculaire concept [8]

Rapid prototyping and fabrication method for 3D food objects

Nanotek patent (Fig. 8) describes a machine with fixed twin extrusion head and a three axis Cartesian construction that can print food product layer by layer. It is a freeform fabrication method for making a three-dimensional food object from a design created on a computer. The method optionally includes an additional step of applying a heat treatment to the 3D shape after this shape is constructed. This method can be used to form an intricate shape of a cake mix, which is then baked [7].

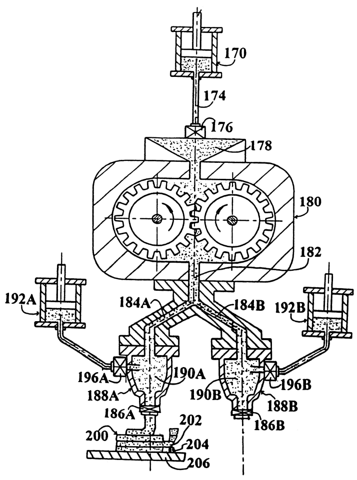

Fig. 8 Nanotek rapid prototyping method for 3D food objects [7]

Virtuoso Mixer Concept

The Virtuoso Mixer (Fig. 9) concept is a process equipment, which works with raw material in order to produce customized food products. The three-level equipment has containers for storing food materials. Top container level controls temperature, humidity and the weight of the product. Top level feeds the middle level of containers, which are comprised of a number of processing tools for mixing, whisking and crushing. Once the food has been processed in the middle level, it is fed into the bottom level of containers, where food is extruded onto the workplace to the required shape [9].

Fig. 9 Virtuoso Mixer concept [10]

3.3. BCN3D+ printer

The BCN3D+ printer (Fig. 3) is a product of RepRapBCN project, where a three dimensional objects are created by additive manufacturing technology. BCN3D+ is an evolution of the previous BCN3D printer, which includes notable improvements on its predecessor. BCN3D+ printer can be operated in two different settings modes – with an extrusion head and with a syringe tool.

Extruder Head

The first mode works with one or two extrusion head end effectors (Fig. 10a). The advantage of this setup is the possibility to apply two different types of material on workplace so the final product may be formed of different kinds of materials in the same processing time. Less weight in the extruder system and improved belt tensioning allow higher speed of movements. BCN3D+ is able to print with almost all existing materials in the wire format of 3 mm diameter. The printing volume with the twin extruder head is 175 mm x 190 mm x 200 mm. On the other hand, it is also possible to print with a single extruder head with a printing volume of 200 mm x 190 mm x 200 mm.

The main advantage of using an extruder end effector is a possibility of continuous printing. The material is being continuously unfolded into an extruder where it is processed and then applied to the workplace. The main disadvantage is the high cost of the steel screw extruder. Another drawback lies in the difficult cleaning of the main workplace of the extruder screw, when it is necessary to change the processed material.

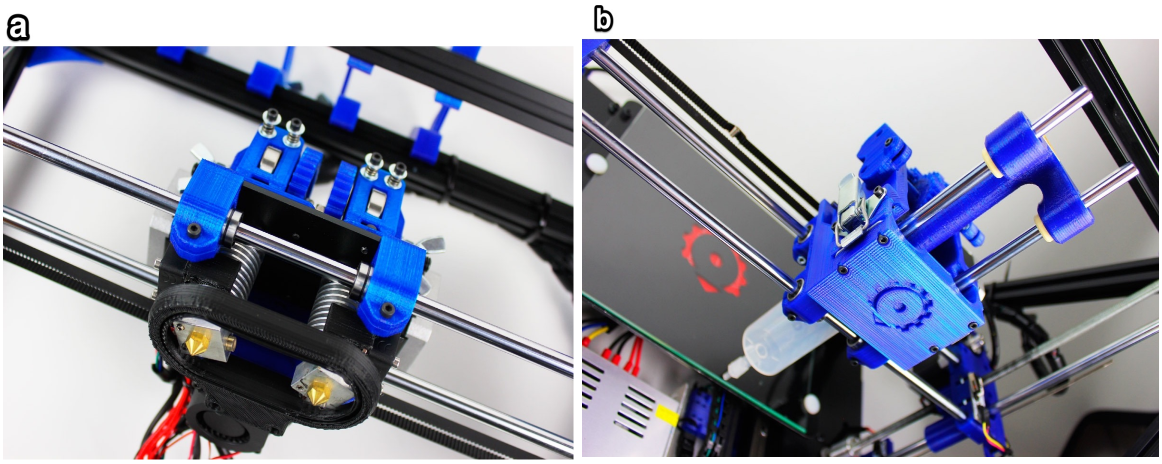

Fig. 10 BCN3D+ printer with extruder and syringe tool end effectors [12]

Syringe tool

The syringe tool end effector (Fig. 10b) is the second printing mode of BCN3D+. This end effector consists of an injection system that controls the amount of material, deposited in syringe tool vessel, by the pressure exerted on the plunger of a syringe tool. With this upgrade the printer can work with soft materials, that is, with all materials that can flow and maintain the shape deposited in successive layers.

The main advantage of this method is its simplicity and versatility. The syringe tool can operate with a wide range of materials. Another benefit relies in the ability to easily control the flow rate of the material by changing the pressure on piston. The main disadvantage is the limited volume of the syringe tool vessel barrel, in case that we need to print larger products. Therefore it is necessary to reconfigure the end effector and fill vessel of syringe tool repeatedly [12].

3.4. Results and motivation

The technique of 3D printing belongs among the newest technologies in recent years. For this reason, there are still many possibilities of extending the use of this technology in various fields and one of these fields is also the food industry. The advantage of 3D printing technology is the possibility of producing a specific product that can be modified during the process itself. This reduces the cost in comparison with conventional manufacturing techniques. 3D printing is preferably used in individual production or small batch production. The range of materials that can be processed by the 3D printer is very wide. The basic material properties are the ability to flow and also to create objects layer by layer. For example, plastics, ceramics, food and many others belong among these materials. 3D printing technology in the food industry aims to enable the production of a product with a specific shape and to satisfy customer needs.

Work on master thesis of mine has been carried out in cooperation with the Fundació CIM - project RepRapBCN, which has developed 3D printer called BCN3D+. In this project, two variants of the end effectors – the extruder and the syringe tool - have been developed. Use of an extruder is preferred mainly due to the possibility of continuous flow of printed material, but the main disadvantages here are the problem with cleaning end effectors workplace and the high cost of manufactured components in the extruder head. Another method is to use a syringe tool. Here, the drawback of difficult cleaning of equipment is eliminated and it is possible to change quickly various materials during printing. On the other hand, there is a drawback caused by the limited volume of the syringe tool vessel. If we want to print larger products, it is often necessary to reconfigure the end effector to fill the vessel of syringe tool repeatedly.

The aim of this master thesis is to provide the design of the system for the food printing that would eliminate the disadvantages of previous variants. Using a pump as the main device for securing correct material flow seems to be the best option. The main benefit of the using a pump should be the price and the simplicity of its design and also the feasibility of the continuous flow of the processed material. Most of the parts of the pump should also be prepared by 3D printing technology, so as to comply with the RepRap concept. It is important to select a pump that could safely and hygienically facilitate the transportation of food, and also ensure that it suits to design and economical use in the system of the 3D printer.

4. Conceptual design and study of alternatives

The main objective of the following section is to provide an overview of techniques and equipment used for pumping materials in the food industry where it is important to observe health and safety regulations and subsequently - according to these regulations – to choose a suitable equipment and features of the device. To select and customize the proper design of the pump, it is necessary to define the properties of the substance to be pumped. In case of pumping food materials, a suitable construction material must be selected to avoid affecting the quality and taste of the pumped material.

4.1. Techniques of continual pumping and pump selection

There is a number of methods of continuous material transportation, so that, at the beginning, it is important to make a simple overview before selecting the right pump for the proposed system. It is also important to define the individual requirements of the system first and then characterize the properties and the structure of each pump. To select any device it is necessary to identify their advantages and drawbacks for transporting the media. At the end of the selection process, the most suitable concept or equipment construction should be chosen.

4.1.1. Types of pumps with continual pumping

Many different pump types exist, but there are two basic principles: rotodynamic and positive displacement. However, in addition to these two categories there are a few other pump designs. Nowadays, the group of dynamic pumps can be further divided into two subgroups. Generally, therefore, the pumps can be divided into four groups according to the type of their construction.

- Rotodynamic pumps
- Special rotodynamic pumps
- Positive displacement pumps
- Other pumps

Pumps are used to transport liquid medium. Liquids differ in chemical composition and physical properties, so that they have different demands for pumping and operational conditions. Because of these widely varying operational requirements, there is a large number of different pump designs available [13].

Rotodynamic pumps

One or more impellers characterize the design of rotodynamic pumps. These impellers are equipped with vanes coming into contact with pumped medium. Rotodynamic pumps are sometimes called radial or axial pumps in the literature and in practice. This designation depends on the main direction in which the liquid flows through the impellers (Fig. 11).

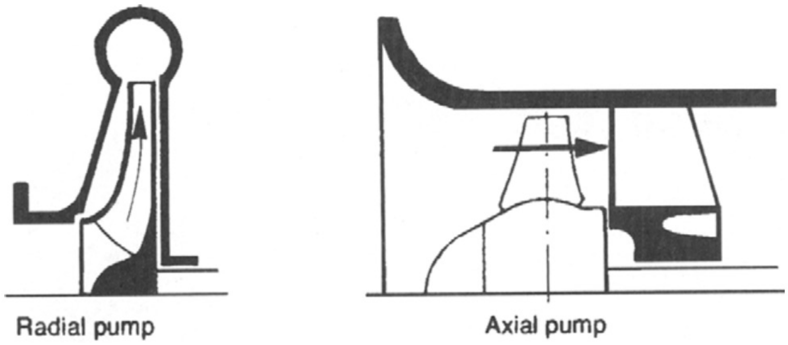

Fig. 11 Rotodynamic pumps design [13]

The performance of pumps is usually shown in the form of a curve (Fig. 12). The main meaning of this curve is the relationship between the volume of liquid transported per unit of time and the pressure increase in the pump system. Volume of transported liquid per unit of time is called flow rate or volume flow. This curve is especially important for the rotodynamic pumps. Typical curve for the radial pump is shown in Figure 12a and the curve for the axial pump in Figure 12b.

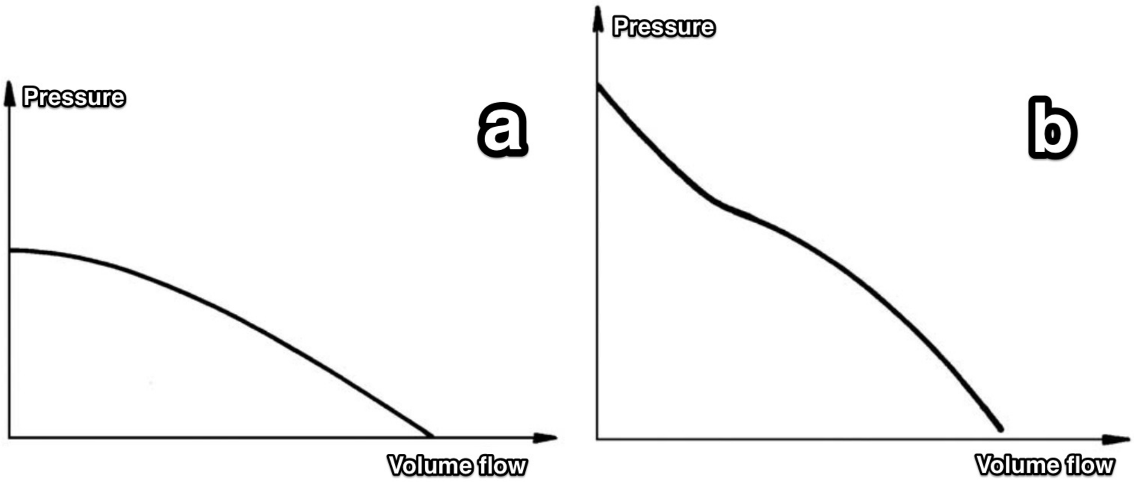

Fig. 12 Pump curves for rotodynamic pumps [14]

According to the curves, pumping a larger amount of medium per unit of time decreases the pressure in the pump system and the associated specific energy supplied to the system. From this characteristic it implies that the rotodynamic pumps are suitable for pumping larger volumes of liquids. However, increasing flow volume produced in the pump implies also a limitation for the choice of types of media to be transported. For instance, pumping suspensions may cause surges in the pump system and the consequent wear by abrasive suspension parts. Therefore, in practice, rotodynamic pump are mainly used for pumping liquids with lower viscosity. The main disadvantages of these pumps are their high cost, difficult cleaning of the pump workplace and difficult sealing the mechanical parts of the pump to prevent the leakage of the pumped media.

Positive displacement pumps

Positive displacement pumps operate with enclosed liquid volumes. Liquids are transported forward in the direction of pumping, or squeezed and expelled into the pump outlet. These pumps operate on completely different principles than rotodynamic pumps and the most important difference is Speed. Speed of the positive displacement pumps tends to be very low in comparison to rotodynamic ones. On the other hand, positive displacement pumps do not rely on speed to develop energy supplied to the system - sufficient pressure to force the liquid into the discharge system. Basically, positive displacement pumps compress the liquid medium from initial condition to discharge conditions and this can be achieved achieve at any speed [13]. This characteristic can be simply described by the pump curve (Fig. 13).

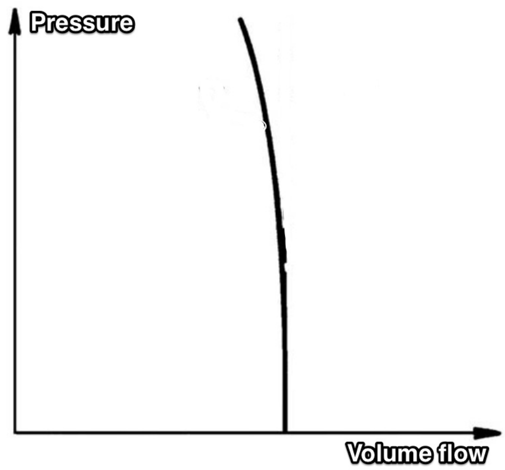

Fig. 13 Pump curve for positive displacement pumps [14]

These characteristics show that positive displacement pumps are suitable for pumping smaller volumes than in case of rotodynamic pumps. Positive displacement pump can favorably achieve high specific energy supplied to the system. These pumps are often also used for precise dosing of liquids.

Special rotodynamic pumps

Special rotodynamic pumps occupy a position between previous two systems. Special rotodynamic pumps have some of the characteristics of rotodynamic the rotodynamic ones and some of the positive displacement ones. Basic idea of the function of these pumps is that they use kinetic energy of liquids but their mechanical structure is different from the rotodynamic pump. Kinetic energy can be transferred to the liquid in increments, by the use of many vanes. Or, alternatively, all energy can be achieved by a single stage [13].

Other pumps

Typical examples of this category are ejectors and airlift pumps. They work on the principle that the pumped liquid is sucked in and mixed with the motive fluid. The overall speed of the fluid flow is reduced and the static pressure is increased in the Venturi jet pump. These types of pumps are useful for priming other pumps [13].

4.1.2. Pumps for food industry

In many parts of the food industry, it is necessary to arrange the transfer of raw materials, intermediate products or final products. For this purpose, a large number of pumps are used in the food industry. The same construction as in most of these pumps is also used in other industries, but very specific requirements are places to the pumps in the food industry, primarily hygienic and safety ones. For particular materials at different stages of processing, specific different kinds of pumps are used. The design of the pump depends on the chemical and physical properties of pumped media. During the pumping, damage or depreciation of the pumped material should be avoided. On the other hand, in some processes, disintegration of the initial material during pumping could be desirable. Main requirements for food pumping applications are that pumps should be efficient, gentle with the product and easily cleanable.

Rotodynamic pumps

Rotodynamic pumps are often used in large food processing plants (Fig. 11 and Fig. 14). The advantage of these pumps is definitely an option to achieve high flow rates, but the disadvantage is their high cost compared to other pumps. Pumped substances include: milk, yogurt, concentrates, butter, oil, and many more. The pumps are therefore especially suitable for pumping large quantities of mostly low-viscosity liquids or suspensions in which, due to high speeds, there is no disintegration of the material components. Stainless steel of approved hygienic quality is usually used as the construction material [13].

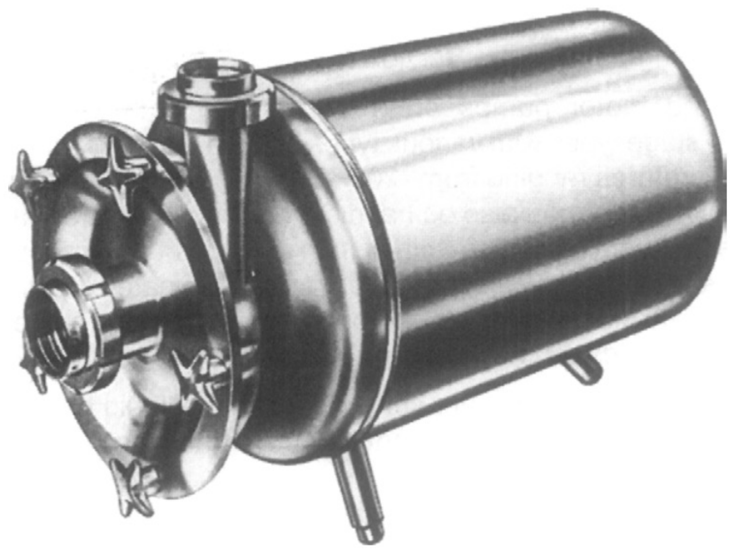

Fig. 14 Rotodynamic pump for food industry [13]

Gear pumps

Gear pump (Fig. 15) belongs to positive displacement pumps group. In the food industry, it is used for instance for pumping fats, oils and concentrates. The pump has a small rotor mounted eccentrically within a larger external gear and when the rotor is driven, the gear also rotates. Gear pumps should be used with care for liquids containing solid particles and slow speed of pumping is recommended. The main disadvantage is that the pump workspace is difficult to seal. For this reason, it is difficult to achieve the necessary hygienic conditions and to clean the pump [13].

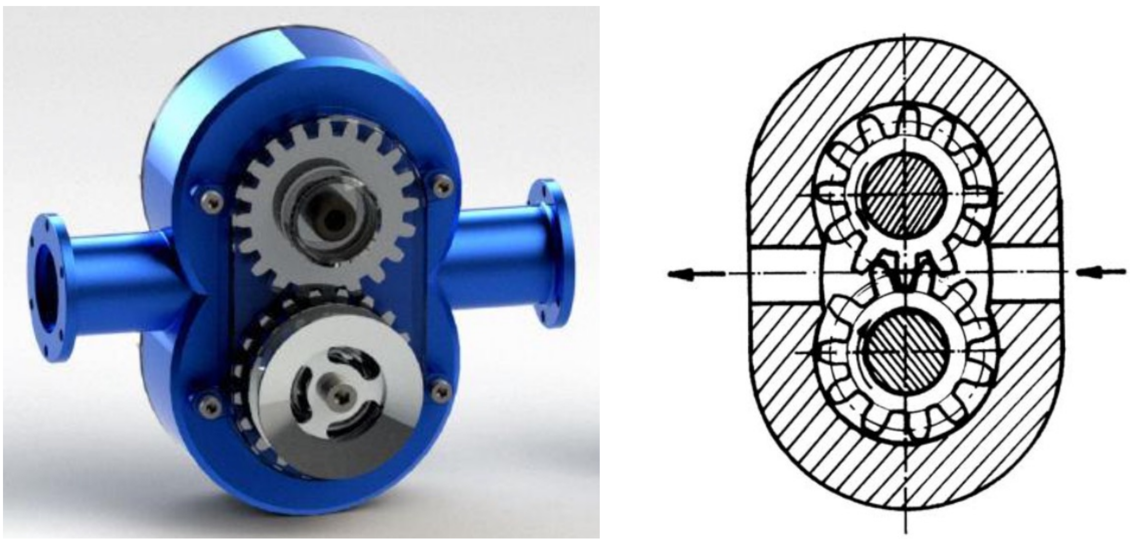

Fig. 15 Gear pump [6] [14]

Lobe pumps

Lobe pumps (Fig. 16) are in many respects similar to the gear pumps but with the difference that they operate without metallic contact of rotors. Synchronized gears, which are completely separated from the pump workspace, drive both rotors. And this separation of the pumped medium from rotor bearings is and advantageous way of how to solve the hygienic problem. These pumps usually operate at relatively low speeds with quiet running and they are often used for high viscosity liquids without the flow pulsation [13].

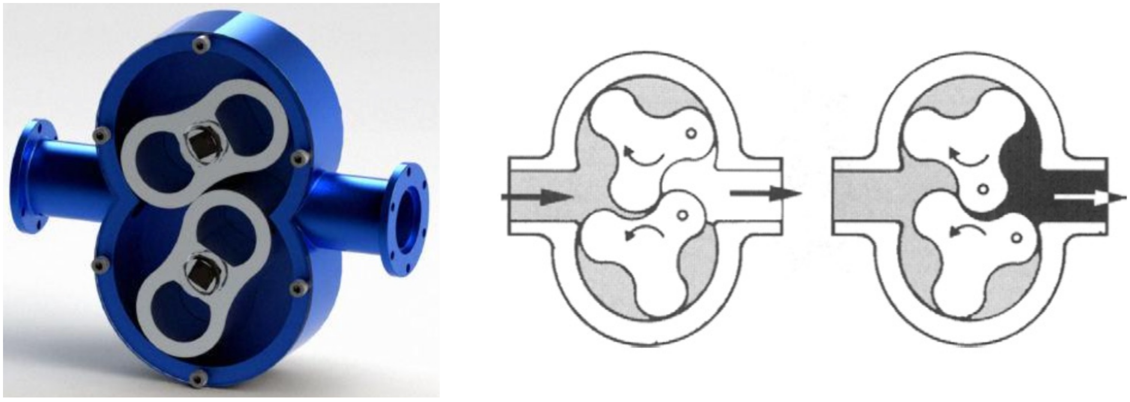

Fig. 16 Lobe pump [6] [13]

Progressive cavity pumps

Progressive cavity pumps (Fig. 17), sometimes called eccentric screw pumps, have only one rotor part. Rotor works within a flexible rubber stator, which has double internal helices. The difference in pitch forms sealed cavities between the rotor and the stator cause an axial flow of the material. Progressive cavity pumps are used for practically all types of liquids from very fluid to highly viscous. The main advantage of these pumps is the possibility of pumping suspensions with abrasive particles but the disadvantage is the possibility of damage to the stator part in the case of using too highly concentrated suspensions [13].

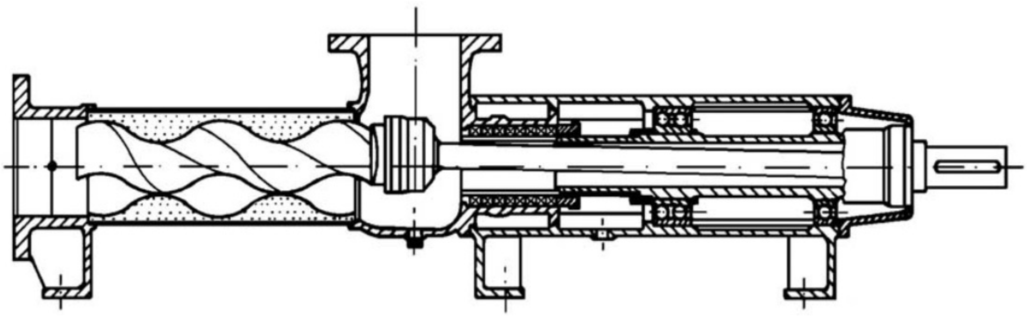

Fig. 17 Progressive cavity pumps [14]

Diaphragm pumps

Piston pumps have stuffing boxes, which are potential areas of leakage. This leakage can be avoided by separating the pumped liquid from the pump workspace. In diaphragm pumps (Fig. 18), separation of the individual spaces is provided by a membrane and the movement of the piston is transmitted directly to this membrane. Diaphragm pumps are used specifically for viscous liquids. Main disadvantage of these pumps is discontinuous flow of pumped material [13].

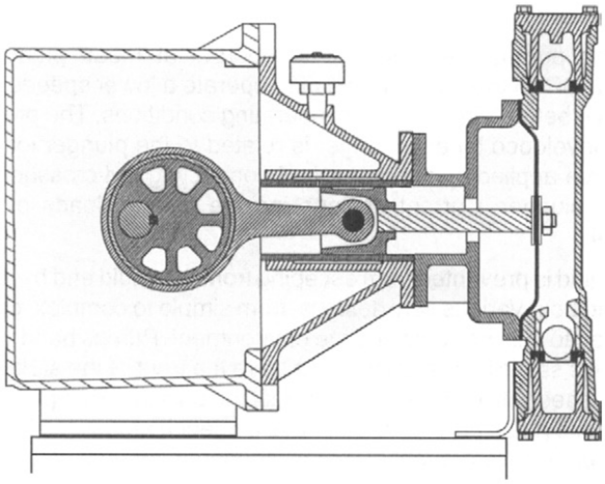

Fig. 18 Diaphragm pump [13]

Peristaltic pumps

Peristaltic pumps (Fig. 19) transport material by mechanically squeezing the space enclosed by the flexible tube. The pump works on the principle of rotating rollers or cams acting directly upon the tube containing the pumped material. Peristaltic pumps are used for all types of liquids and also suspensions with abrasive particles. Main advantage is that the pumped medium is completely enclosed with no possibility of leakage except in the case of a tube failure. Another advantage is the continuous pumping of the material and also a low cost of the equipment [13].

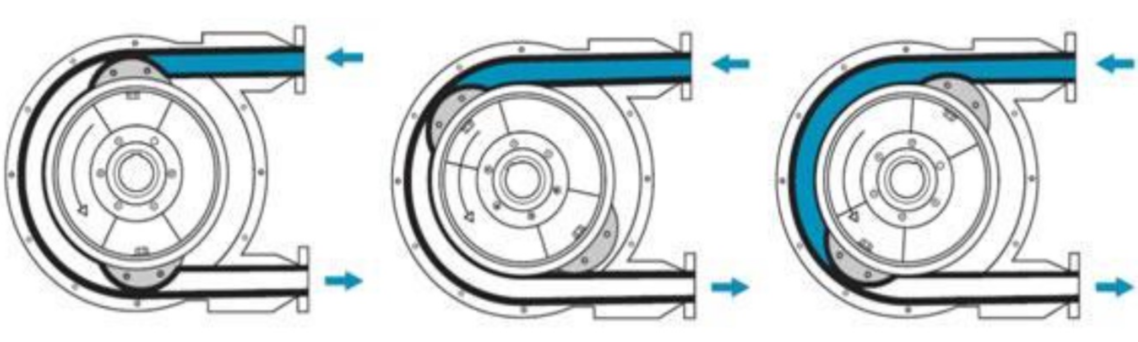

Fig. 19 Peristaltic pump [6]

4.1.3. Operating conditions

The correct pump selection is important to ensure proper and efficient function of the system in which the pump is installed. Suitable choice of pump is made when all properties most suited to the application are assessed. The factors that most influence the selection of pumps are:

- Required flow rate
- Process temperature
- Liquid viscosity
- Suction pressure
- Discharge pressure
- Properties of the liquid

Required flow rate should be seen from two points of view, firstly from long-term changes and then also from short-term fluctuations. On these aspects depends subsequent choice of control methods with different initial costs and running efficiencies depending on frequency of the flow rate changes. The liquid density varies with temperature and this aspect can affect the conversion to pressure for example in rotodynamic pumps. Viscosity of the processed medium is one of the most important factors in pumping but viscosity also depends on many other process factors. The liquid viscosity varies considerably with temperature. Various types of pumps are differentially sensitive to the viscosity of the liquid. Some pumps rely on viscosity for lubrication, other pumps rely on viscosity for sealing and some pumps are unaffected by viscosity. The effect of system suction and discharge pressure changes on the pump flow rate of material can be extremely important. From the curves of pressures in paragraph 3.1.1 it can be seen that positive displacement pumps can provide a constant flow rate in a wide range of pressure changes. This feature may be important and can simplify flow rate control methods. Comparison of pressure characteristics is as important as that of economic effects of the use of a positive displacement pump or rotodynamic pumps. The properties of liquids are especially important for choosing the correct type of pump. The main properties are: viscosity of the pumped medium, resistance to a chemical attack, variations in the rate of the chemical reaction with temperature and the possibility of medium contamination. Some pumps may be resistant to chemical compounds over a short-time period but they can be damaged over a long-time period and this factor is mainly important in sanitation. The physical composition of the pumped media has of course also a strong influence on the process. In case that solid particles or suspensions are pumped, it is important to take into account the difference between the abrasive and non-abrasive materials.

Due to the influence of abrasive particles, the lifetime of the equipment can be strongly affected [13].

4.1.4. Pump selection

In previous chapters, the classification of different types of pumps based on their structure and functions of the process has been described. There are many pumps and pumped substances factors that affect the entire system, in which the pump is installed. For these reasons, it is highly important to choose the right kinds of pumps. The aim of this master thesis is to select and design a pump device allowing the main force for the transporting material in 3D printers for food.

All food processes are demanding on health and safety regulations. For this reason, it is necessary to select a pump in which no contamination of the pumped food will take place and cleaning of the pump workspace will be easy. It is also important to consider what will be the best pump design requirements for achieving a certain continuous flow rate. It is needed to consider the variability of the device because of the possibility of using different types of pumped food. Another factor influencing the choice of equipment is its cost, which must correspond to the overall function of the 3D printer.

Taking into account the previously mentioned factors, using a peristaltic pump seems to be the most appropriate option. Large number of peristaltic pumps are nowadays used for example in medicine for the pumping of blood or in the chemical industry for accurate dosing substances into the fermenters, since one of the main factors of peristaltic pumps is their hygienic safety and accuracy of operation. In case of 3D printers we can almost completely eliminate the use of rotodynamic pumps because of they work with small volume flow rate only. For 3D printing technique is important to ensure a continuous flow of media and even this condition peristaltic pumps provides. Another great advantage is variability in the use of different kinds of food for printing and the ability to work with both liquids and with high-viscosity suspensions. In economic terms, peristaltic pump appears as appropriate. A large number of components of the peristaltic pump can be produced also by the technique of 3D printing. The aim is to focus on the main design parameters needed to ensure the construction of a peristaltic pump for use in food print.

4.2. Characterization of pumped materials

The substances occur in three physical states in nature: the solid state, the liquid state and gaseous state. To describe the materials to be used in 3D printing technology, it is necessary to focus on two following states only: solids and liquids. In the case of the 3D printing technology, it is only possible to use highly viscous liquids which after applying the printed material to the workplace, will solidify quickly and thus create a solid structured product. It is also possible to focus on the suspension with small solid particles. Physical properties of these substances needed for 3D printing are the ability to form solid structure and therefore the ability to create 3D products layer by layer. Therefore, we cannot consider the use of the gaseous state substances. The properties of these liquids substances vary greatly. Characteristics of liquids should be known in case of pumping. The main characteristic parameters are:

- Changes of state
- Viscosity
- Density
- Compressibility
- pH value

In the case of 3D printing it is necessary to ensure that, during the processing and printing, the material is in a liquid state, transportable through the pump and pumped system of the printer. In the following application of the material to the working space, it is however necessary that the material solidifies as soon as possible. For this reason, it is necessary to know the phase diagram of the printed materials.

The effect of viscosity and density of the pumped system has already been described in paragraph 3.1.3, but since the viscosity is very important in the design of the pump in the system, it needs to be a bit more specific. Generally, the viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. Between two layers of a liquid flowing at different speeds, shear stress and tangential resistance are developed. This is caused by the molecular effect. In the case of 3D printing technology it can be assumed that during the process only laminar flow of printed material is present, for which viscosity is defined by Newton's Law

$$\tau = \mu \cdot \dot{\gamma} = \mu \cdot \frac{\Delta v}{\Delta y} \tag{1}$$

where Δv $[\mathrm{m \cdot s^{-1}}]$ is change of viscosity, Δy $[\mathrm{m}]$ is the distance between layers, τ $[\mathrm{N \cdot m^{-2}}]$ is shear stress and μ $[\mathrm{Pa \cdot s}]$ is dynamic viscosity.

The liquids that follow the law in laminar flow and have constant viscosity are called Newtonian liquids: those not fulfilling these requirements are denoted as non-Newtonian ones. Most of suspensions and high molecular liquids belong to non-Newtonian liquids. The characteristics of these liquids are shown in Fig. 20.

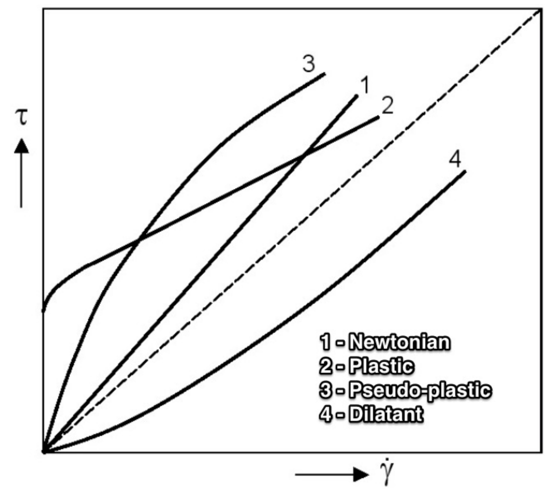

Fig. 20 Newtonian and non-Newtonian liquids [14]

Another important characteristic of liquids is the compressibility, which is a measure of the relative volume change of a fluid or solid as a response to the pressure and temperature. In case of rotodynamic pumps, considering of compressibility can be neglected but in case of positive displacement pumps it must be quantified. Compressibility is defined by a relation

$$Compressibility = \frac{1}{K} \tag{2}$$

where K $[\mathrm{N} \cdot \mathrm{m}^{-2}]$ is the bulk modulus of the liquid.

The bulk modulus is defined

$$K = \rho \cdot \frac{\Delta p}{\Delta \rho} = -V \cdot \frac{\Delta p}{\Delta V} \tag{3}$$

where ρ $[\mathrm{kg} \cdot \mathrm{m}^{-3}]$ is the density of the pumped liquid, Δ is the change of magnitude, p $[\mathrm{Pa}]$ is the liquid pressure and V $[\mathrm{m}^3]$ is the volume of the pumped liquid.

The pH value is a measure of acidity or basicity of substances. The pH value depends on concentration of hydrogen ions H^* $[\mathrm{mol} \cdot \mathrm{l}^{-1}]$ and value is defined

$$pH = \log_{10} \frac{1}{H^*} \tag{4}$$

Acid solutions have pH values between 0 to 6.5, neutral 6.5 to 7.5 and alkaline 7.5 to 14. The pH value of the processed material is a very important parameter to select the proper material for equipment construction, because the processed material can affect properties and surface structure of the equipment (Fig. 21). With regard to pH it is therefore necessary to choose a suitable material of equipment construction that will withstand the effects of corrosion and resist the wide range of chemical compounds [13].

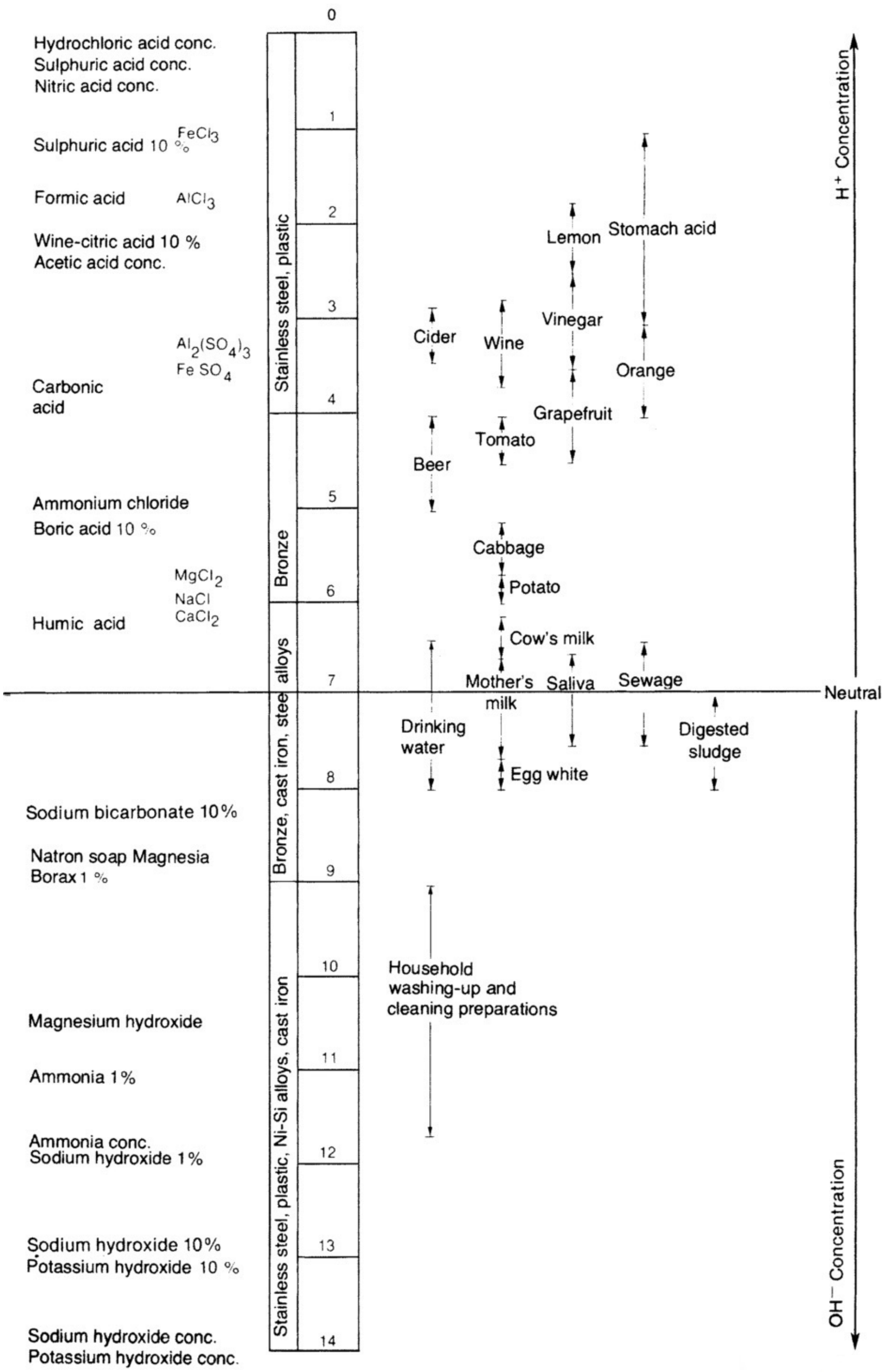

Fig. 21 Effect of pH value [13]

4.3. Characterization of pump materials

In selection of the material for construction it is necessary to choose a comprehensive solution with respect to hygiene and safety and also in terms of design characteristics. From this perspective, plastic seems to be the best construction material. Many of plastic materials are nowadays used for transporting equipment and packaging containers in the food industry, because:

- Plastics are flowable and moldable under certain conditions
- Plastics are generally chemically inert
- Plastics are cost effective and lightweight
- Plastics provide choices in respect of transparency, color, heat resistance and barrier

The advantage of peristaltic pumps is the possibility of total separation of the processed material from the working parts of the pump, so it is possible to use more types of construction materials. The tube, which is in contact with the processed material, must be hygienically safe and nonhazardous not to damage the quality and taste of the material. On the other hand, in selection of the material for the construction of the pump, it is necessary to choose a plastic that can be extruded on a 3D printer. Nowadays, peristaltic pumps are often used in chemical, pharmaceutical and food industry, so there is no problem to find suitable tubing for them. In case of food industry, for example SEBS (styrene-ethylene/butylene-styrene), PTFE (polytetrafluoroethylene) are used. However, plastics most often used for food industry tubing are thermoplastic elastomer. Thermoplastics elastomers exhibit a broad chemical compatibility, especially resistance to strong acids, alkalis and oxidizing agents. They have small water absorption, can be operated at higher pressures up to $10\ bars$ and at temperatures ranging from 5 to $80°C$ [15].

4.4. Characteristics of pumps and piping system

During the transport the flow of liquids is driven by the energy that is required to activate the movement of the liquid to overcome the resistance and the local height and pressure differentials in the flow direction. For the positive displacement pump, the conversion of mechanical energy into pressure takes place directly in the working element of the pump. The working element of the peristaltic pumps is designed mostly as a roller or cam. The fluid pressure in the working chamber of the pump is hydrostatic and is independent of the kinematic values of the flow field, that is, velocity and position. The working elements of the peristaltic pump move cyclically, resulting in the slight pulsation of the pumped liquid. Increasing the number of elements can minimize this pulsation.

The characteristics calculations of the pumps and piping are normally used in the height form of Bernoulli equation

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} + g \cdot z_1 = \frac{p_2}{\rho} + \frac{v_2^2}{2} + g \cdot z_2 + \frac{\Delta p_f}{\rho} \tag{5}$$

where p $[\mathrm{Pa}]$ is the static pressure, ρ $[\mathrm{kg} \cdot \mathrm{m}^{-3}]$ is the density of the pumped material, v $[\mathrm{m} \cdot \mathrm{s}^{-1}]$ is the velocity of the pumped material, g $[\mathrm{m} \cdot \mathrm{s}^{-2}]$ is the gravitational acceleration, z $[\mathrm{m}]$ is the height above datum and Δp_f $[\mathrm{Pa}]$ is the frictional pressure head loss. Scheme of the basic characteristics calculation is shown in Figure 22.

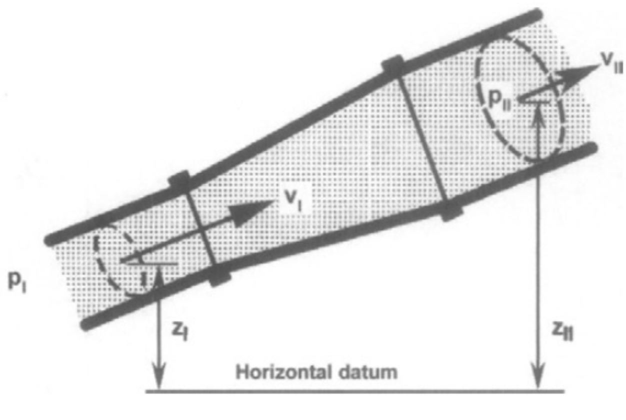

Fig. 22 Application of Bernoulli equation [13]

The continuity equation is a statement for the condition that mass is not created or destroyed during a flow of material. This equation, which is based on the assumption that the flow is steady, has the form

$$Q = v_1 \cdot A_1 = v_2 \cdot A_2 \tag{6}$$

where Q $[\mathrm{m}^3 \cdot \mathrm{s}^{-1}]$ is the volume flow and A $[\mathrm{m}^2]$ is the cross-sectional area of the tube.

To express the frictional pressure loss, it is preferable to express Bernoulli equation (5) in terms of head meters of liquid column

$$\frac{p_1}{\rho \cdot g} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\rho \cdot g} + \frac{v_2^2}{2g} + z_2 + \frac{\Delta p_f}{\rho \cdot g} \tag{7}$$

The last term in this equation is called head loss h_f $[\mathrm{m}]$

$$h_f = \frac{\Delta p_f}{\rho \cdot g} \tag{8}$$

The head loss can be used to define losses in straight pipes

$$h_f = \lambda \cdot \frac{l}{d} \cdot \frac{v^2}{2g} \tag{9}$$

where λ $[-]$ is the loss coefficient for straight pipes, l $[\mathrm{m}]$ is the length of pipe and d $[\mathrm{m}]$ is the pipe diameter. The loss coefficient depends on Reynolds number and also on internal roughness of the pipe, which depends on the material and condition of pipe. In case of peristaltic pumps it is necessary to define minor head losses in bends. These losses can be calculated with the help of the formula

$$h_f = \xi \cdot \frac{v^2}{2g} \tag{10}$$

where ξ $[-]$ is the minor loss coefficient of the bend. These coefficients are tabulated for various sizes of bend structures. It depends on the bending angle and also on the ratio of the tube diameter and bend radius. When connected with a pipe system, the pump will operate at a point of equilibrium between the pump and the pipe system. To ensure the proper functioning of the pumps in the system of 3D printers, pump energy is required to cover these mentioned friction losses that occur in the system. For a given pipework system of l and d, the loss coefficients λ and ξ are often independent of volume flow for large values of the Reynolds Number. The loss of head then becomes approximately

$$h_f = constant \cdot Q^2 \tag{11}$$

The system differential head H_{syst} is usually divided into a static component H_{stat}, which results from a Bernoulli equation, and a loss component

$$H_{syst} = H_{stat} + h_f \tag{12}$$

The static component, which is generally independent of the flow, can be deduced from the Bernoulli equation (7)

$$H_{stat} = \frac{p_2 - p_1}{\rho \cdot g} + h \tag{13}$$

where h [m] is the difference in elevation. Then we can provide the system performance in relation to flow (Fig. 23). Required flow can then determine the operating point of the pump depending on the characteristics of the system.

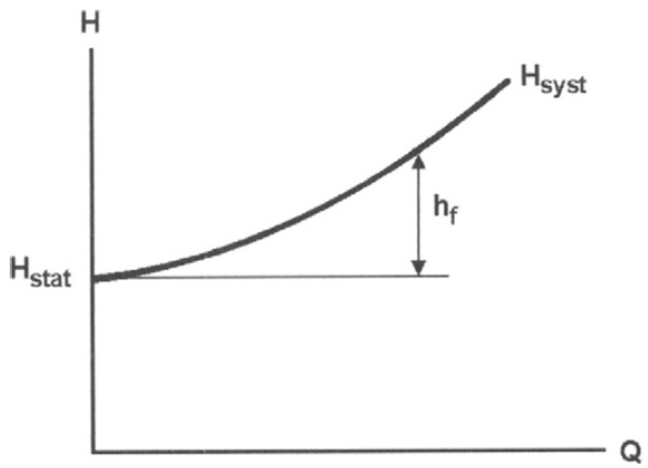

Fig. 23 System curve [13]

4.5. Food life cycle, food assessment and safety issues

Increasing food market segmentation and global food supply chains operate with sophisticated food distribution systems. Figure 24 shows the distribution flow of food from the farms to the consumer through several sublevels. Important aspects of the transport of raw food materials are hygienic regulations and maintaining the quality of these products. With growing number of sublevels in transportation, increases the risk of damage to food products and, naturally, also the amount of product spoilage and wastage increase. So, great emphasis is placed on improving the transport of food products. Nowadays, many customers are interested in raw products with the final product processing carried out by themselves.

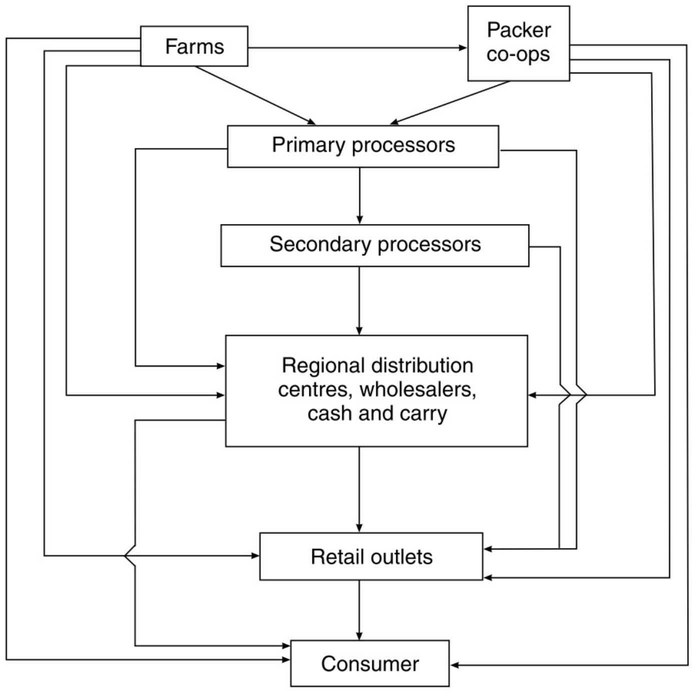

Fig. 24 Food distribution system [16]

To maintain food quality and safety, it is needed to ensure preservation and to prevent biodeterioration. Physical contamination may be caused by enzymes and microorganisms which could be responsible for food biodeterioration. Enzymes are naturally present in foods products and they can potentially catalyze reactions that could lead to food biodeterioration. In some cases this action of enzymes can be used in the manufacture of hard cheese for example: usually, however, it is necessary to inactivate these enzymes. Also microorganisms can play a very important role in breaking down organic material. These microorganisms include all small living organisms that are not visible for human eye. And for that reason, food preservation is aimed at extending the shelf life of foods. In most cases, it is the growth of microorganisms and the action of naturally occurring enzymes that limit the length of food life cycle. There are many methods that can be applied to preserve foods, and commonly a combination of several individual methods is used. The most important and most widely used methods are [16]:

- High temperature
- Blanching
- Thermal processing
- Pasteurization
- Low temperature – freezing, chilling and cooling
- Drying and water activity control
- Chemical preservation
- Modifying the atmosphere
- High pressure processing
- Irradiation

4.6. Results of concept design

The correct pump selection is important to ensure proper and efficient function of the system in which the pump is installed. Taking into account all factors needed for proper pumping a food material, using a peristaltic pump seems to be the most appropriate option. In case of the 3D printers, we can almost completely eliminate the use of rotodynamic pumps because they work with small volume flow rate only. For 3D printing technique it is important to ensure a continuous flow of media and even this condition peristaltic pumps provide. Another great advantage is their variability in the use of different kinds of food for printing and the ability to work with both liquids and high-viscosity suspensions. In economic terms, peristaltic pump appears as appropriate. A large number of components of the peristaltic pump can be produced also by the technique of the 3D printing. To describe the materials to be used in the 3D printing technology, we can focus on solid and liquid states only. Needed physical properties of these substances are the ability to form solid structure and therefore the ability to create 3D products layer by layer. In selection the material of construction it is necessary to choose a comprehensive solution in hygiene and safety and also in terms of design characteristics. From this perspective, plastic seems to be the best construction material. The plastics most often used for food industry tubing are thermoplastic elastomers. They show a broad chemical compatibility, especially resistance to strong acids, alkalis and oxidizing agents.

5. Detail design

The main objective of the following section is to design the basic parameters of the pump according on the selected operating requirements and, therefore, with help of the modeling software, to provide 3D model and manufacturing drawings of individual peristaltic pump components.

5.1. Characteristics of pump

The pump must be able to cover losses in the piping system. Continuity equation was used to calculate losses, Darcy-Weisbach equation was utilized for friction losses and then were used equations for the minor losses and for calculating the friction coefficient λ [14].

Before designing the construction of the pump it is necessary to choose the basic operational and construction parameters. The sugar solution is selected as the basic medium for the calculation of pump design. Dynamic viscosity of $80\ \mathrm{wt.\%}$ sugar solution at $25\ ^{\circ}\mathrm{C}$ is $10.2\ \mathrm{Pa \cdot s}$. The density of water at the same temperature is $997\ \mathrm{kg \cdot m^{-3}}$ and density of sugar is $1\ 600\ \mathrm{kg \cdot m^{-3}}$. As the value of volumetric flow of printed material was chosen $10\ \mathrm{cm^{3} \cdot min^{-1}}$. To calculate the characteristic of the pump, it is required to select a basic design parameters: $7\ \mathrm{cm}$ was chosen as a bending diameter of the peristaltic pump tube, $4.8\ \mathrm{mm}$ as the internal diameter of the tube, $8\ \mathrm{mm}$ as the external diameter of tube, $0.8\ \mathrm{m}$ as the length of the tube and $180°$ as the angle between input and output of the peristaltic pump. To calculate losses in the system it is necessary to define the effect of narrowing the extrusion head. The diameter of the outlet part of the extruder head is $1\ \mathrm{mm}$. The detailed parameters are shown in Table 2. Figure 25 shows the scheme with the main construction dimensions.

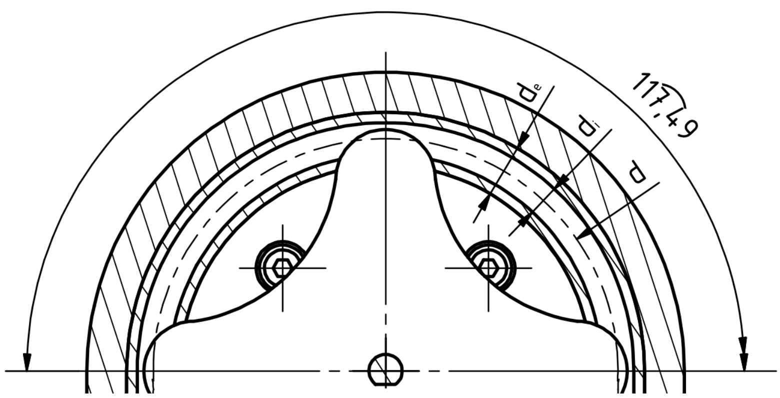

Fig. 25 Scheme with construction dimensions

Table. 2. Operational and construction parameters

$\rho_w = 997\ \mathrm{kg \cdot m^{-3}}$	Water density ($T = 25$ °C) [17]
$\rho_s = 1\ 600\ \mathrm{kg \cdot m^{-3}}$	Sugar density [17]
$\mu_m = 10.2\ \mathrm{Pa \cdot s}$	Sugar solution dynamic viscosity ($T = 25$ °C, 80 wt. %) [17]
$Q = 10\ \mathrm{cm^3 \cdot min^{-1}}$	Volumetric flow
$d = 70\ \mathrm{mm}$	Bending diameter
$d_i = 4.8\ \mathrm{mm}$	Tube internal diameter [15]
$d_e = 8\ \mathrm{mm}$	Tube external diameter [15]
$l = 800\ \mathrm{mm}$	Tube length
$\alpha = 180°$	Angle between input and output
$d_o = 1\ \mathrm{mm}$	Extruder head outlet diameter

The minimum power that peristaltic pump produces must be in equilibrium with the minimum power needed to compensate the losses of the system. The constraints are that the pump must pump at least $10\ \mathrm{cm^3 \cdot min^{-1}}$ to a height of $25\ \mathrm{cm}$. The velocity of the fluid in the tubing can be derived from the equation (6)

$$v = \frac{Q}{A_1} = \frac{\frac{10}{10^6 \cdot 60}}{\frac{\pi \cdot \left(\frac{4.8}{10^3}\right)^2}{4}} = 0.01\ \mathrm{m \cdot s^{-1}} \tag{14}$$

where $A_1[\mathrm{m^2}]$ is tube internal sectional area. To define the Reynolds number, it is necessary to express density of sugar solution [13]

$$\rho_m = \rho_w + \frac{c_m \cdot (\rho_s - \rho_w)}{100} = 997 + \frac{80 \cdot (1\ 600 - 997)}{100} = 1\ 479\ \mathrm{kg \cdot m^{-3}} \tag{15}$$

where c_m $[-]$ is the mass concentration. The Reynolds number can be calculated according to

$$Re = \frac{v \cdot d_i \cdot \rho_m}{\mu_m} = \frac{0.01 \cdot \frac{4.8}{10^3} \cdot 1\ 479}{10.2} = 0.01 \tag{16}$$

The Reynolds number indicates that the flow is in a laminar state. The Darcy–Weisbach equation, which relates to the head loss, contains a dimensionless friction factor λ, known as the Darcy friction factor. To calculate the friction factor it is possible to use Moody diagram (Fig. 26) with help of Reynolds number and the constant A, which assumes a value of 64 for the tubular profile.

$$\lambda = \frac{A}{Re} = \frac{64}{0.01} = 9\,976.01 \tag{17}$$

Using this friction factor, head loss can be derived from equations (8) and (9)

$$\Delta p_{f1} = \lambda \cdot \frac{l}{d_i} \cdot \frac{v^2}{2} \cdot \rho_m = 9\,976.01 \cdot \frac{0.8}{\frac{4.8}{10^3}} \cdot \frac{0.01^2}{2} \cdot 1\,479 = 104.437\ \mathrm{kPa} \tag{18}$$

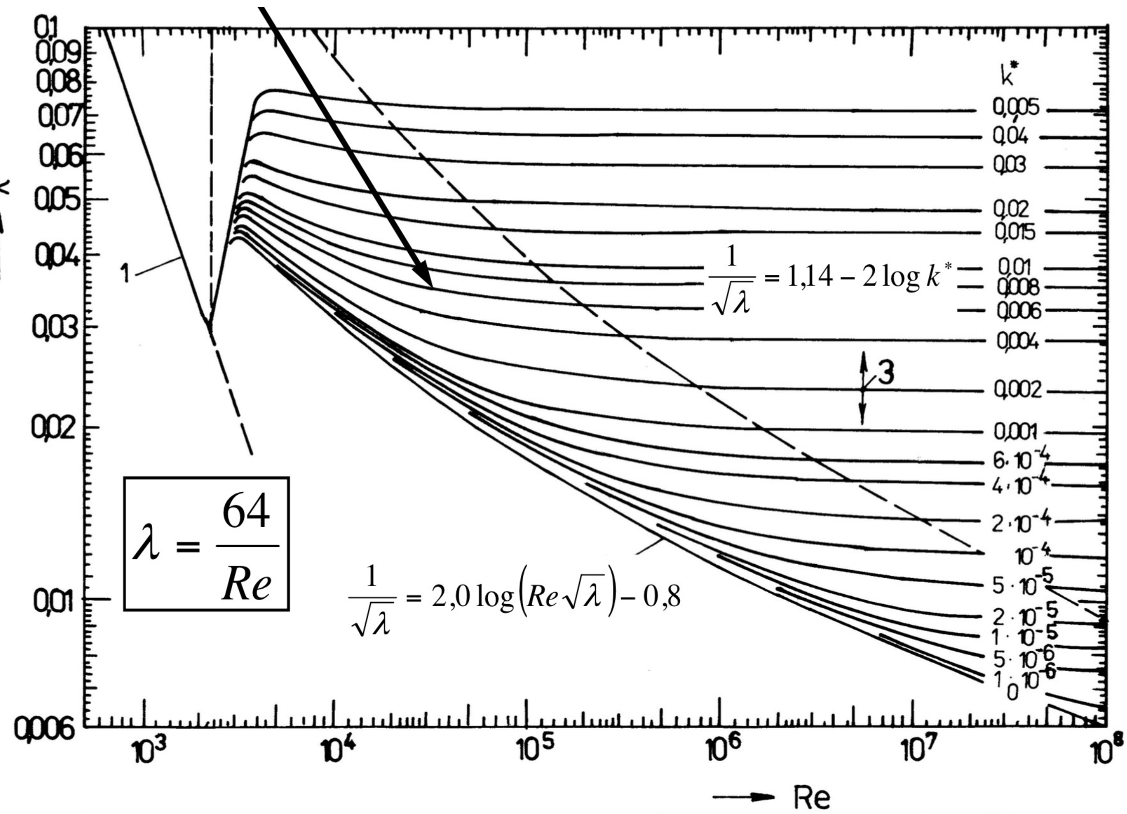

Fig. 26 Moody diagram [14]

Minor head losses can be calculated with help of the bending minor losses coefficient in peristaltic pump (coefficient ξ_1) and minor losses due to the narrowing of the profile (coefficient ξ_2) in the extruder head. The bending minor losses consist of bending loss caused by changing the direction (coefficient ξ_b) and the friction loss (coefficient ξ_f). The coefficient of bending loss caused by changing the direction is defined by

$$\xi_b = \lambda \cdot \frac{l_p}{d_i} = \lambda \cdot \frac{\pi \cdot \frac{d}{2}}{d_i} = 9\,976.01 \cdot \frac{\pi \cdot \frac{0.07}{2}}{\frac{4.8}{10^3}} = 228\,524.81 \tag{19}$$

where l_p $[\mathrm{m}]$ is the length of the tube in peristaltic pump. The friction loss coefficient is defined by

$$\xi_f = 0.21 \cdot \left(\frac{\frac{d}{2}}{d_i}\right)^{-\frac{1}{2}} = 0.21 \cdot \left(\frac{\frac{0.07}{2}}{\frac{4.8}{10^3}}\right)^{-\frac{1}{2}} = 0.08 \tag{20}$$

The banding minor losses coefficient can be derived from equations (19) and (20)

$$\xi_1 = \xi_b + \xi_f = 228\,524.81 + 0.08 = 228\,524.89 \tag{21}$$

Minor losses coefficient which describes losses due to the narrowing of the profile in extruder head output is defined by

$$\xi_2 = 0.5 \cdot \left(1 - \frac{S_0}{S_i}\right) = 0.5 \cdot \left(1 - \frac{\frac{\pi \cdot 1^2}{4}}{\frac{\pi \cdot 4.8^2}{4}}\right) = 0.48 \tag{22}$$

Minor head losses can be derived from the equations (8), (10), (21) and (22)

$$\Delta P_{f2} = (\xi_1 + \xi_2) \cdot \frac{v^2}{2} \cdot \rho_m = (228\,524.89 + 0.48) \cdot \frac{0.01^2}{2} \cdot 1\,479 = 14.354\ \mathrm{kPa} \tag{23}$$

The total loss is the sum of friction head loss (18) and minor head loss (23)

$$\Delta p_f = \Delta p_{f1} + \Delta p_{f2} = 104.437 + 14.354 = 118.791\ \mathrm{kPa} \tag{24}$$

The pressure at the output from the extrusion head, p_2 is supposed to assume a value of $10\ \mathrm{kPa}$ and the speed of the printed medium in entire system is constant. The pressure which must be delivered by the pump can be derived from equations (7) and (24)

$$\frac{p_{pump}}{\rho_m \cdot g} + \frac{v_1^2}{2 \cdot g} + z_1 = \frac{p_2}{\rho_m \cdot g} + \frac{v_2^2}{2 \cdot g} + z_2 + \frac{\Delta p_f}{\rho_m \cdot g} \tag{25}$$

$$p_{pump} = (z_2 - z_1) \cdot g \cdot \rho_m + p_2 + \Delta p_f \tag{26}$$

$$p_{pump} = 0.25 \cdot 9.81 \cdot 1\,479 + 10\,000 + 118\,791 = 132.42\ \mathrm{kPa}$$

Taking into account that any other pumped material used has a higher density and viscosity, it is necessary to consider higher pressure demands on the system. Therefore, for further calculation, the pressure supplied by the pump to the system, p_{pump}, is considered to assume a value of $200\ \mathrm{kPa}$. It is possible to calculate an ideal power to compensate the losses and to get characteristics for proper work of the pump. Ideal power can be defined by

$$P_{ideal} = p_{pump} \cdot Q = 200\ 000 \cdot \frac{10}{10^6 \cdot 60} = 0.03\ \mathrm{W} \tag{27}$$

However, ideal power does not take into account the fact that pump is not $100\ \%$ efficient. Estimating an efficiency of $\eta = 20\ \%$, true power can be defined by

$$P_{actual} = \frac{P_{ideal}}{\eta} = \frac{0.03}{0.2} = 0.17\ \mathrm{W} \tag{28}$$

To ensure a proper operation of the pump, a stepper motor NEMA 17 SY42STH47-1684A has been chosen, which is also used for the movement of all axes of the BCN3D+ printer. The specification of the stepper motor is shown in Table 3.

Table 3. NEMA 17 specifications [18]

General specifications		Electrical specifications	
Step Angle (°)	1.8	Rated Voltage (V)	2.8
Temperature Rise (°C)	80 Max (rated current 2 phase on)	Rated Current (A)	1.68
Ambient temperature (°C)	-20～+50	Resistance Per Phase (±10%Ω)	1.65 (25°C)
Number of Phase	2	Inductance Per Phase (±20%mH)	2.8
Insulation Resistance	100MΩ, Min (500VDC)	Holding Torque (Kg.cm)	4.4
Insulation Class	Class B	Detent Torque (g.cm)	200
Max.radial force (N)	28 (20mm from the flange)	Rotor Inertia (g.cm²)	68
Max.axial force (N)	10	Weight (Kg)	0.365

Mechanical power of the stepper motor can be calculated with help of the rated current I $[\mathrm{A}]$, number of phase f $[-]$ and the rated voltage U $[\mathrm{V}]$

$$P_{motor} = I \cdot U \cdot f = 1.68 \cdot 2.8 \cdot 2 = 9.4\ \mathrm{W} \tag{29}$$

Comparing equations (28) and (29) implies that the engine power is sufficient to meet the requirements for proper pump work [6].

The minimum distance between the rotating part and the housing of the peristaltic pump determines the maximum squeeze applied on the tubing. The amount of the squeeze applied to the tubing affects the performance of pump and the tube life. Maximum squeezing decreases the tubing life dramatically, while less squeezing decreases the pumping efficiency. Therefore, the amount of squeeze becomes an important design parameter. The amount of squeeze is expressed as a percentage of twice the wall thickness

$$y = \frac{2 \cdot t - b}{2 \cdot t} \cdot 100 \tag{30}$$

where t $[\mathrm{m}]$ is the wall thickness of the tubing and b $[\mathrm{m}]$ is the minimum distance between the rotating part and the housing of the peristaltic pump. The amount of squeeze is typically 10 to 20 %, depending on the softness of the tube material and on the characteristic of the pumped material. Taking into account pumping a food material, 10 % amount of squeeze is chosen. The minimum distance between the rotating part and the housing of the peristaltic pump can be derived from equation (30)

$$\begin{aligned} b &= 2 \cdot t \cdot \left(1 - \frac{y}{100}\right) = 2 \cdot \frac{d_e - d_i}{2} \cdot \left(1 - \frac{y}{100}\right) = \\ &= 2 \cdot \frac{8 - 4.8}{2} \cdot \left(1 - \frac{10}{100}\right) = 2.56\ \mathrm{mm} \end{aligned} \tag{31}$$

However, taking into account the accuracy of the printing technique, the minimum distance b is supposed to assume a value of $2.6\ \mathrm{mm}$. Figure 27 shows the scheme with the calculated minimum distance between the rotating part and the housing of the peristaltic pump.

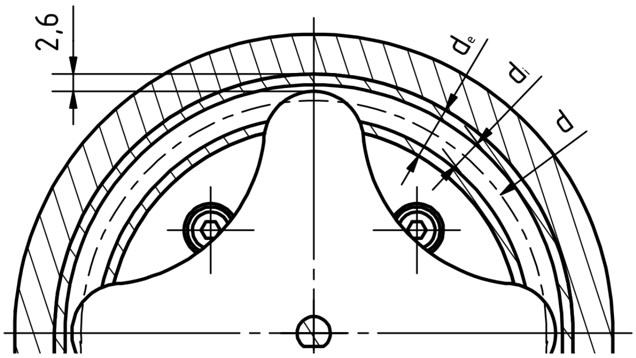

Fig. 27 Scheme of a pump construction

To ensure a proper volume flow of the pumped material, it is necessary to calculate the speed of the pump rotation

$$n = \frac{Q}{V_w} = \frac{Q}{l_p \cdot S_i} = \frac{\frac{10}{10^6 \cdot 60}}{\pi \cdot \frac{0.07}{2} \cdot \frac{\pi \cdot 0.0048^2}{4}} = 0.08\ \mathrm{s}^{-1} = 5\ \mathrm{min}^{-1} \tag{32}$$

where V_w $[\mathrm{m}^3]$ is the workspace volume in the peristaltic pump [14].

5.2. Design of peristaltic pump

The pump design was created in the 3D Autodesk Inventor 2015 modeling system. For each component of the peristaltic pump, a 3D model was created followed by a detailed manufacturing drawing. In the construction of each component, an emphasis was laid on respecting calculated structural parameters, on the simplicity of construction and on the possibility of producing individual parts of the pump by the 3D printing technique. Therefore, most of the components are made of plastic material. As the joining components, those were selected which are already used in the construction of the BCN3D+ printer. The overall construction of the peristaltic pump was designed to fit into the concept of RepRap 3D printers. Figures 28-32 show the final construction of peristaltic pump.

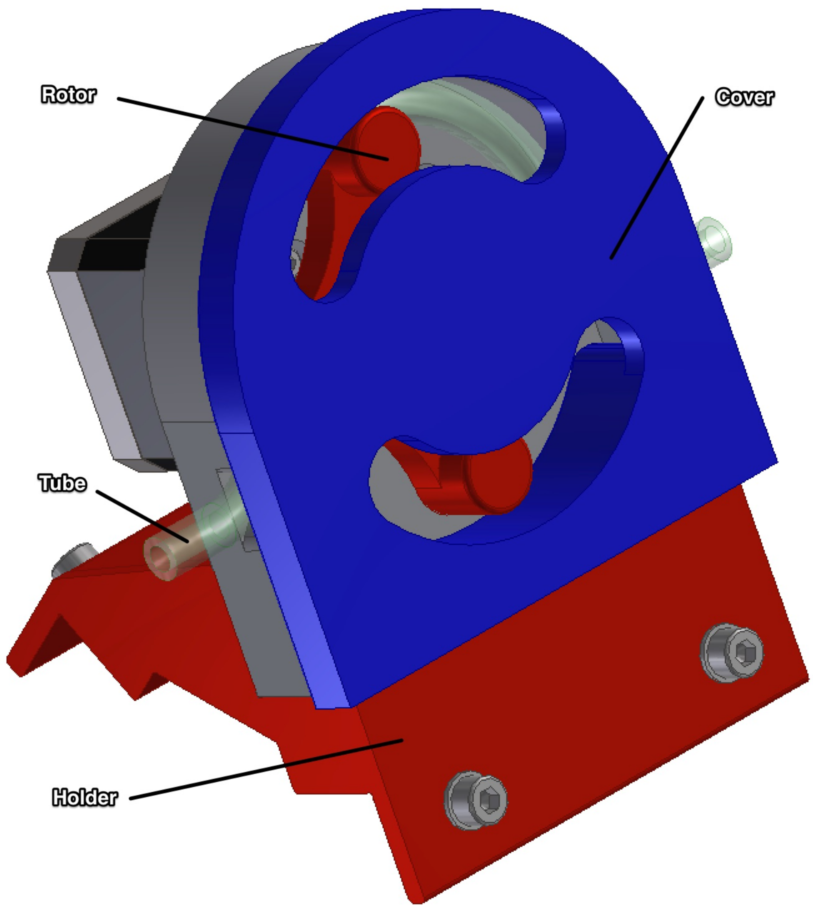

Fig. 28 Peristaltic pump for BCN3D+ printer

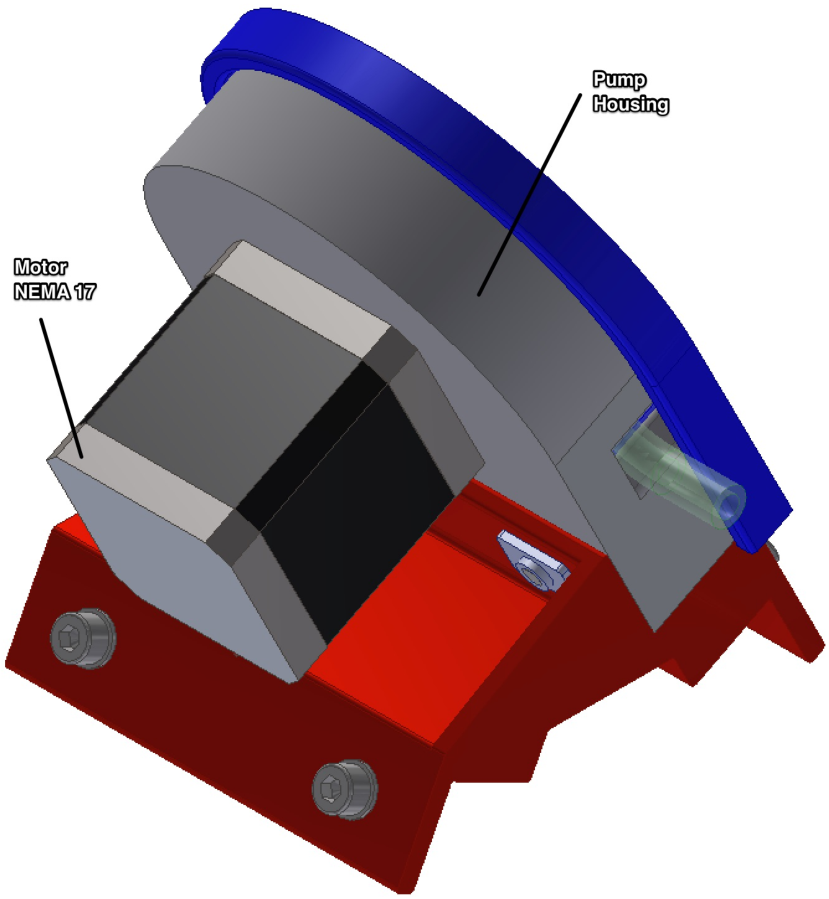

Fig. 29 Peristaltic pump for BCN3D+ printer

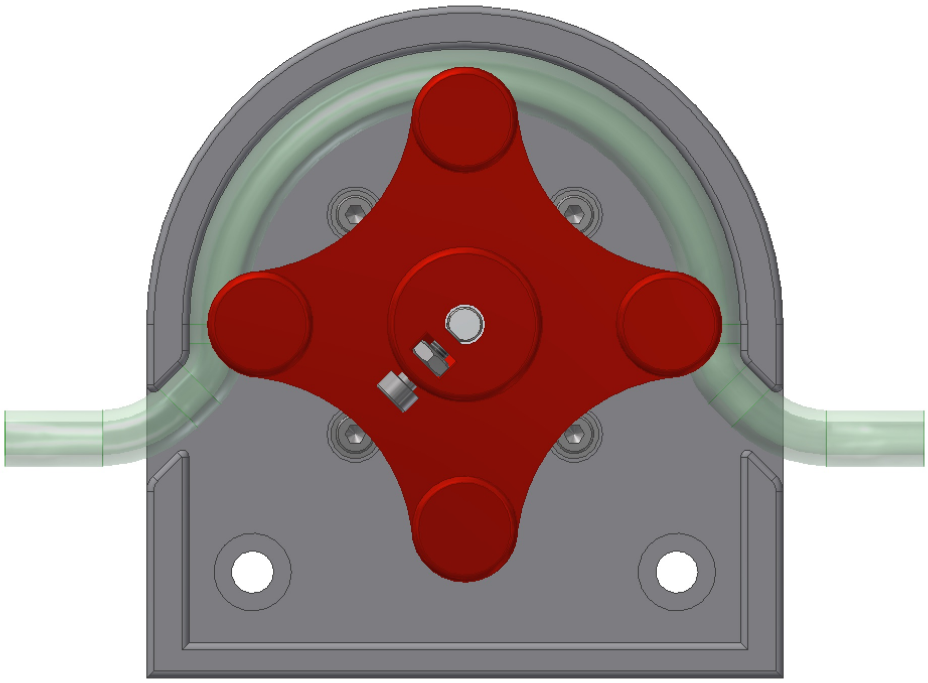

Fig. 30 Peristaltic pump for BCN3D+ printer

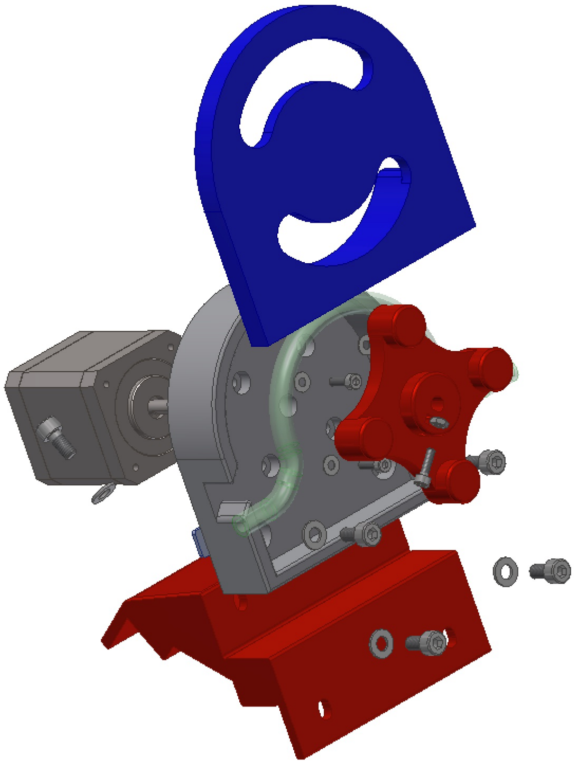

Fig. 31 Peristaltic pump for BCN3D+ printer

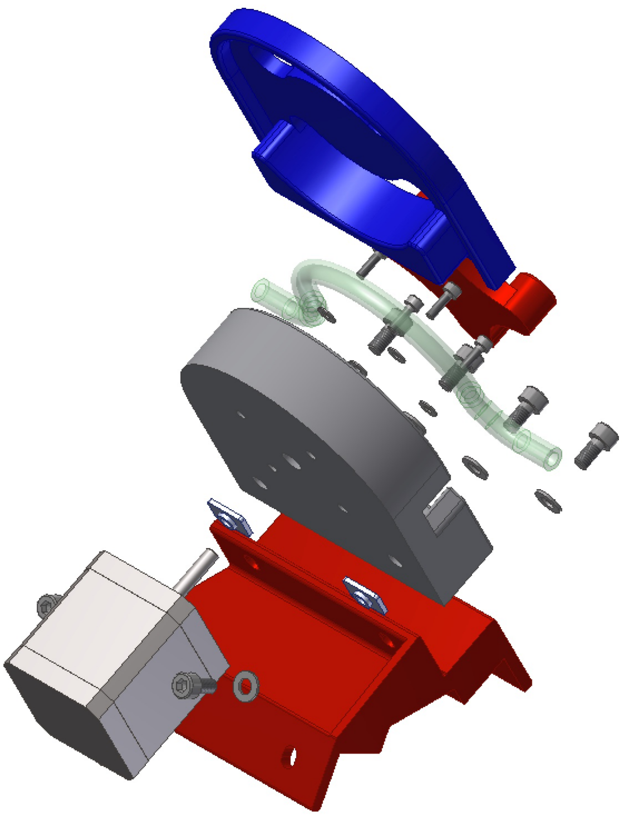

Fig. 32 Peristaltic pump for BCN3D+ printer

5.2.1. Holder

The holder (Fig. 33) was designed so that it can be attached on the top of the printer. The upper part was chosen so as to make the access to and operation with the pump easy. To attach the holder, four screws and nuts were applied, which are already used in the construction of the printer. Specifically, four pieces of screw DIN 912 M5x10, four pieces of washers DIN 125 M5 and four pieces of nuts HNKK5-5.

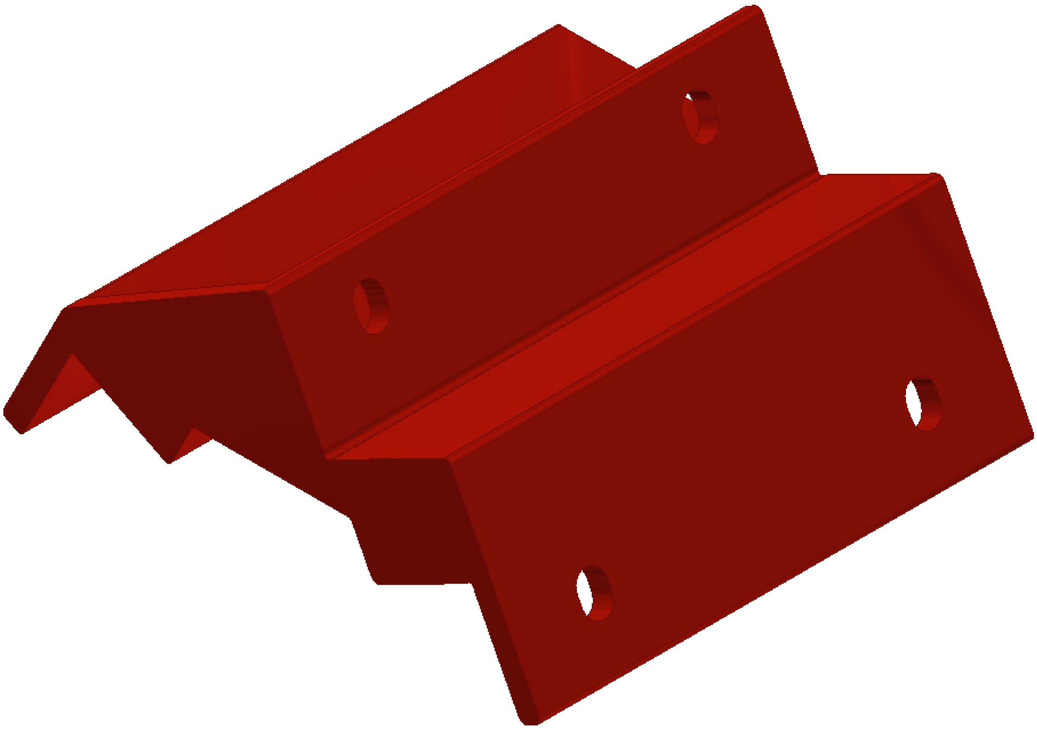

Fig. 33 Holder

5.2.2. Pump housing

The pump housing (Fig. 34) is one of the most important elements of the pump. It is constructed so that it can be attached to the holder and, at the same time, to a motor. To attach the housing to the holder, two pieces of screws DIN 912 M5x10, two pieces of washers DIN 125 M5 and two pieces of nuts HNKK5-5 were used. To attach the engine, four pieces of screws DIN 912 M3x10 and four pieces of washers DIN 125 M3 were used. Furthermore, the pump has been designed so as to meet the basic dimensional conditions that have been designed in section 5.1.

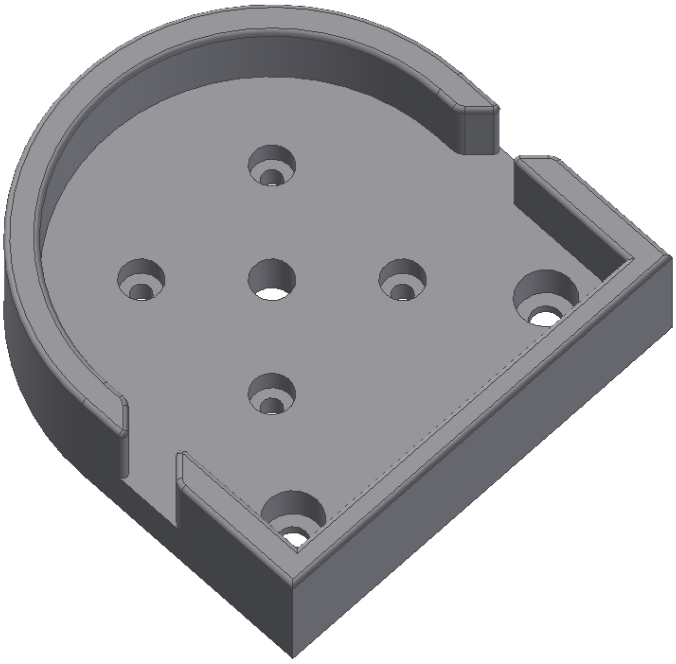

Fig. 34 Pump housing

5.2.3. Cover

The cover (Fig. 35) only meets the safety function, preventing foreign parts from entering the rotation part of the pump; however, due to the low speed there is no danger to the health of the user. Furthermore, the cover offers protection against pulling out of the tube from the working area of the pump. There is an emphasis on its simplicity, when it is not appropriate to use additional joining components.

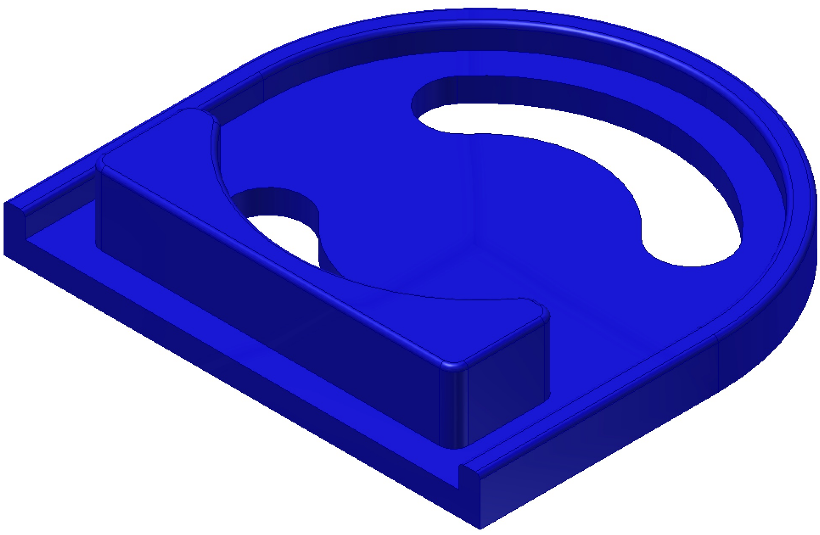

Fig. 35 Cover

5.2.4. Rotor

In the rotor structure, emphasis was laid on ensuring a continuous flow of the pump, while maintaining the dimension proposed in section 5.1. For this reason, four acting rotor elements were designed, being in the contact with squeezed tubing. Two versions of the rotor were designed. The first version (Fig. 34) is designed to avoid friction between the rotor and the tubing, which is ensured by rotating cylinders. However, for the manufacturing of the rotor, this variant is relatively complicated.

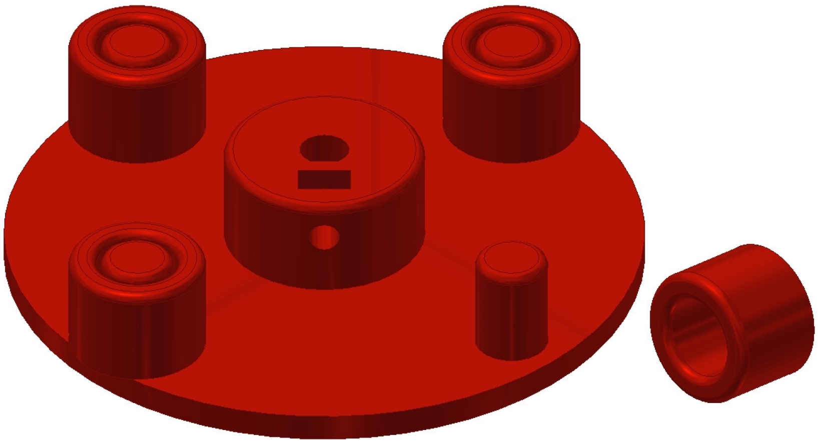

Fig. 36 Rotor variant 1

From this point of view, the other version of the rotor (Fig. 37) consists of only one part. Taking into account the low pump speed, it is possible to neglect the damage arising from the friction between rotor and tubing. Therefore, for the final design of the pump, the second rotor version was chosen. To attach the rotor to the motor, screw DIN 912 M3x10 and nut DIN 555 M3 were used.

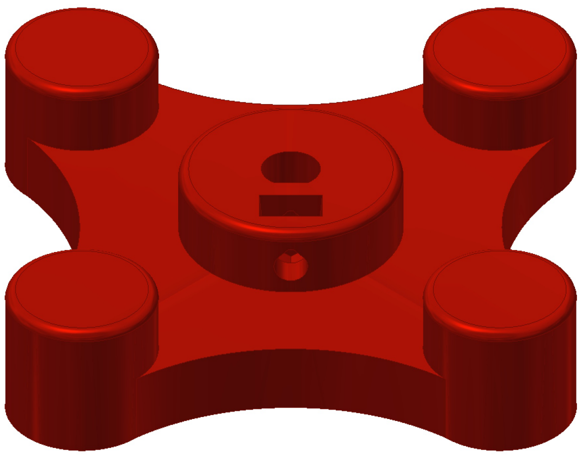

Fig. 37 Rotor variant 2

5.2.5. BCN3D+ with peristaltic pump

Figure 38 and 39 shows the attachment of the peristaltic pump on the BCN3D+ printer. The design of the BCN3D+ printer has been created by Fundació CIM.

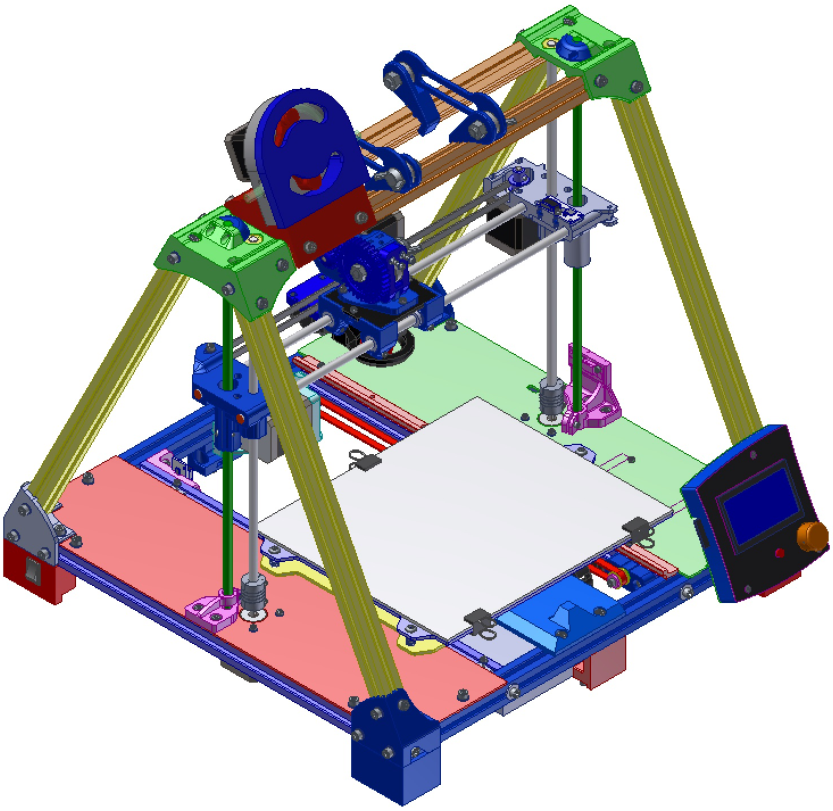

Fig. 38 BCN3D+ with peristaltic pump

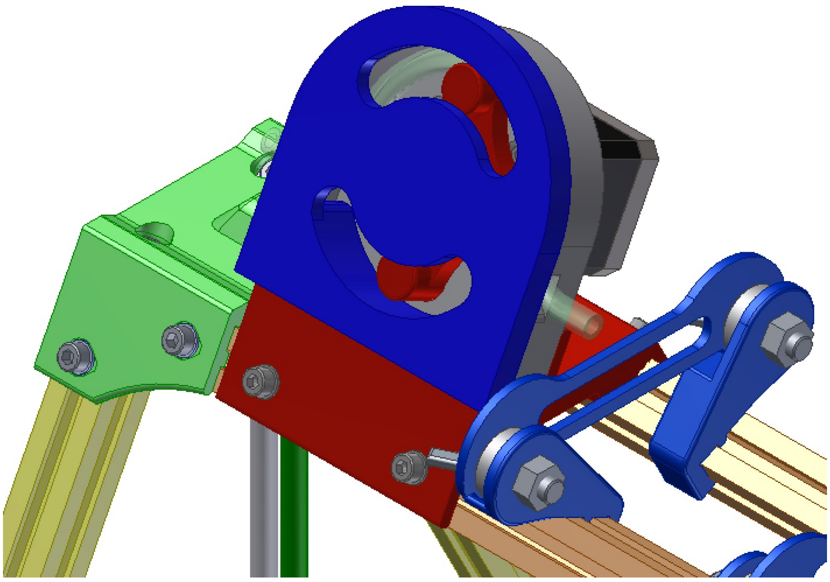

Fig. 39 BCN3D+ with peristaltic pump

6. Production drawings

No.	Description	Material	Quantity
1	Motor NEMA 17 SY42STH47-1684A		1
2	Pump housing	PLA	1
3	Rotor	PLA	1
4	Cover	PLA	1
5	Holder	PLA	1
6	DIN 125 M5		6
7	DIN 125 M3		4
8	DIN 912 M5x10		6
9	DIN 912 M3x10		5
10	Tube Ø 4,8 x 1,6 - 800	Silicone	1
11	Nut HNKK5-5	Steel	6
12	DIN 555 M3		1

Annexe 1: Manufacturing drawing, PERISTALTIC PUMP: VB01-01.0000

Annexe 2: Manufacturing drawing, HOLDER: VB01-01.0001

Annexe 3: Manufacturing drawing, PUMP HOUSING: VB01-01.0002

Annexe 4: Manufacturing drawing, COVER: VB01-01.0003

Annexe 5: Manufacturing drawing, ROTOR: VB01-01.0004

7. Images

For each component of the peristaltic pump, a real model in the BCN3D+ printer was processed. As the joining components, those were selected which are already used in the construction of the BCN3D+ printer. Figure 40 show the final construction of the peristaltic pump.

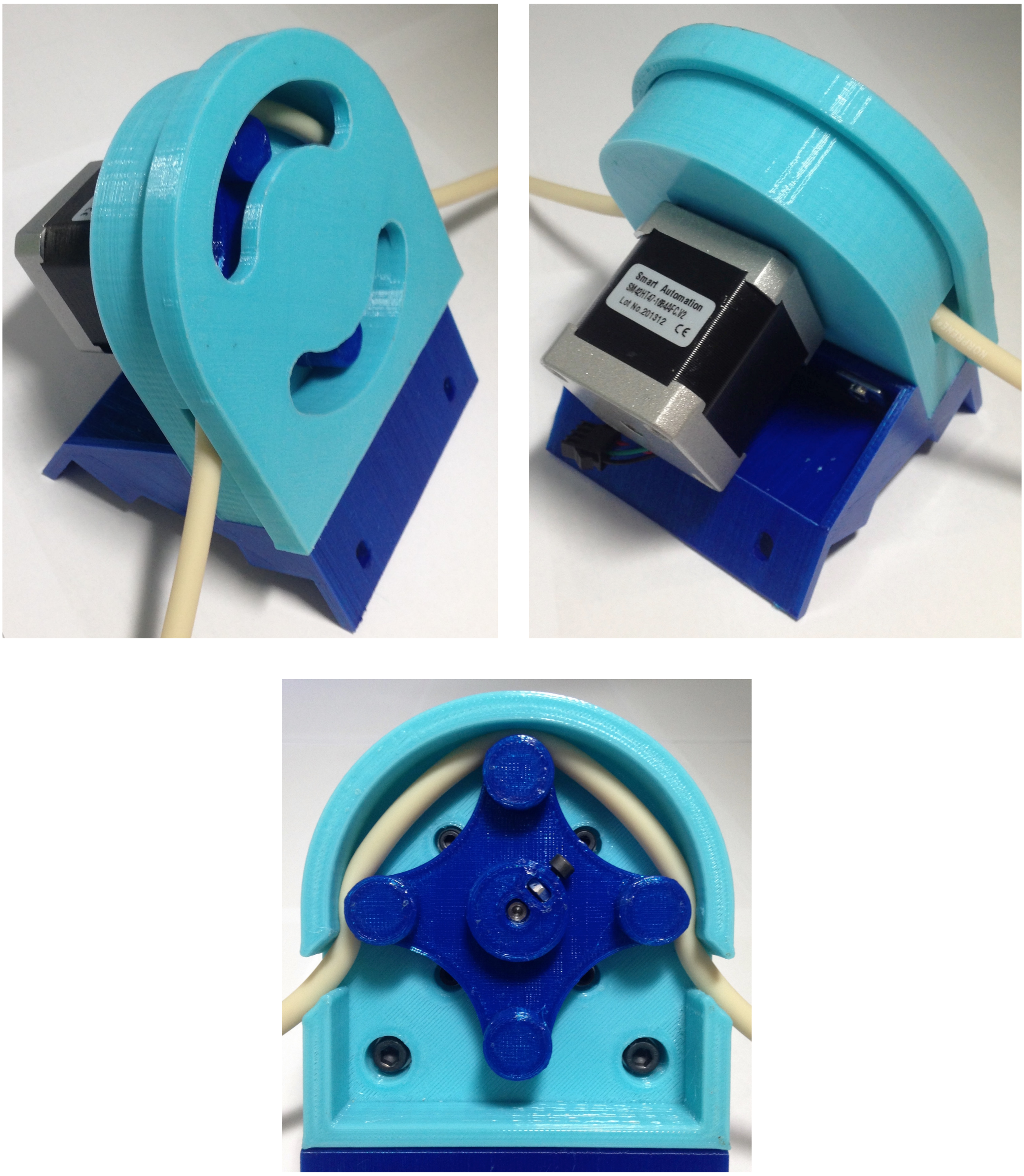

Fig. 40 Construction of the peristaltic pump

8. Feasibility study

Each product must meet the requirements of the European Parliament directives. Compliance with these directives was necessary during the elaboration of the whole project. Subsequently, a study of economic suitability of the project has been elaborated and the expected return of the investment has been estimated.

8.1. Environmental impact

The environmental impact assessment of the project is governed by DIRECTIVE 2014/52/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 April 2014. This directive defines the environmental impact as:

"Directive 2011/92/EU of the European Parliament and of the Council has harmonized the principles for the environmental impact assessment of projects by introducing minimum requirements, with regard to the type of projects subject to assessment, the main obligations of developers, the content of the assessment and the participation of the competent authorities and the public, and it contributes to a high level of protection of the environment and human health. Member States are free to lay down more stringent protective measures in accordance with the Treaty on the Functioning of the European Union."

The principles of this Directive are complied with during the realization of the entire project. The easiest material to print with, PLA, is biodegradable and odorless. This material is melts at low temperature, approximately $50\ °C$ so the energy consumption is relatively small. Also, the accuracy of the 3D print technology is high so that it eliminates problems with waste management. The environmental impact assessment is a process during which the effects of the given projects on the physical and social environment are identified and evaluated. Environmental issues have an increasing importance for the society and must be taken into account to preserve the environment.

8.2. Economical costs

For the economic study of the project, two concepts have been examined; the costs associated with engineering and design on the one hand and the estimated cost of the product including material and manufacturing on the other. At the end of the study, an estimate of the return of investment for this project has been prepared. As to the cost of research, hours spent and invested in developing the prototype were considered. All these costs are included in the design costs which are a special kind of development cost that arises from design and implementation of innovations. The design costs (Table 4.) will in proportion be charged as manufacturing overhead on the involved manufacturing jobs according to the regulations of the foundation.

Table 4. Design costs

	[h]	[€/h]	Total cost
Senior engineer	4	80	320,00 €
Junior engineer	32	40	1 280,00 €
Internist	270	10	2 700,00 €
		TOTAL	**4 300,00 €**

Since the construction of the pump consists only of normalized components and components that can be printed on the 3D printer, the manufacturing costs do not vary depending on the production volume. For this reason, the model costs are of the same price as the final product ones. Material costs (Table 5.) consist of normalized components and plastic materials which are the major components of the product. On the other hand, normalized components have the highest influence on the material costs.

Table 5. Material costs

Component	Quantity	Magnitude	Unit cost	Magnitude	Total cost
Step motor	1	unit	11,95	€	11,95 €
Pump Housing	130	g	0,02	€/g	2,60 €
Rotor	31	g	0,02	€/g	0,62 €
Cover	72	g	0,02	€/g	1,44 €
Holder	132	g	0,02	€/g	2,64 €
Normalized components	29	unit	0,02	€/unit	0,58 €
Tubing	800	mm	22	€/m	17,60 €
				TOTAL	**37,43 €**

The planned price of the product is 80 € and in the six months after the placing product on the market it is planned to sell ten products each month. In the second half of the first year, monthly sales are expected to increase by further ten products. Generally, this corresponds to 20 % of the total sales of the 3D printers. This means that for the first year after the placing product on the market it is planned to sell 180 products. In the second year, the sales will stabilize at twenty-five products each month, meaning 300 products every year. Production costs are expenses that come into being at the production and services and they are influenced differently. Therefore they are usually divided into fixed costs and variable costs. The production costs are calculated from the hourly wage per product. Production overhead costs are calculated from 10 % and special direct costs from 5 % of hourly wage. The prices for advertising depend on the size of the company and the size of the market. In this case, advertising costs are considered as 20 % of initial costs [6].

Table 6. Indicators of economic viability

Year	**0**	**1**	**2**	**3**
Sold units	0	180	300	300
Design costs	4 300,00 €			
Material costs	37,43 €	6 737,40 €	11 229,00 €	11 229,00 €
Production costs (per product)		10,00 €	10,00 €	10,00 €
Production overhead costs (per product)		1,00 €	1,00 €	1,00 €
Special direct costs of production (per product)		0,50 €	0,50 €	0,50 €
Production costs		2 070,00 €	3 450,00 €	3 450,00 €
Advertising costs	869,79 €			
Sales		14 400,00 €	24 000,00 €	24 000,00 €
Profit before tax (PBT)		5 592,60 €	9 321,00 €	9 321,00 €
Taxes (30 %)		1 677,78 €	2 796,30 €	2 796,30 €
Profit after tax (PAT)		3 914,82 €	6 524,70 €	6 524,70 €
Cash flow	-5 207,22 €	3 914,82 €	6 524,70 €	6 524,70 €
Accumulated cash flow	-5 207,22 €	-1 292,40 €	5 232,30 €	11 757,00 €
Net present value (NET), i = 5 %	4 439,28 €			
Payback	1.1 years			

For the calculation of the net present value, a discount rate of 5 % is chosen. With the help of the economic viability indicator (Table 6.), it is calculated that the return of the investment is 1.1 years from placing the product on the market.

9. Conclusions

The aim of this master thesis is to provide the design of the system for the food printing that would eliminate the disadvantages of previous variants. Using a peristaltic pump as the main device for securing correct material flow seems to be the best option. The main benefit of the peristaltic pump is the price and the simplicity of its design. For the 3D printing technique it is important to ensure a continuous flow of media and even this condition is provided by peristaltic pumps. Another great advantage is their variability in the use of different kinds of food for printing and the ability to work with both liquids and high-viscosity suspensions.

In the selection of the construction material it is necessary to choose a comprehensive solution in hygiene, safety and also in terms of design characteristics. From this perspective, plastic seems to be the best construction material. The plastics most often used for food industry tubing are thermoplastic elastomers. They show a broad chemical compatibility, especially resistance to strong acids, alkalis and oxidizing agents.

The pump design was created in the 3D Autodesk Inventor 2015 modeling system. For each component of the peristaltic pump, the 3D model was created, followed by detailed manufacturing drawing. In the construction of each component, is an emphasis was laid on complying with calculated structural parameters, on the simplicity of construction and on the possibility of producing individual parts of the pump by the 3D printing technique. Therefore, most of the components are made of plastic material. As the joining components, those were selected which are already used in the construction of the BCN3D+ printer. The overall construction of the peristaltic pump was designed so as to fit into the concept of the RepRap 3D printers.

Each product must meet the requirements of the European Parliament directives, and this is fulfilled for all designed products. Compliance with these directives is necessary during the realization of the whole project. Subsequently, a study of economic suitability of the project has been elaborated and the expected return of the investment was estimated. The costs associated with engineering and design costs 4 300,00 € and the cost of the product including material and manufacturing costs 37,43 €. The net present value, with 5 % rate, is 4 439,28 € in two years from placing the product on the market. With the help of the economic viability indicator it has been calculated that the return of the investment is 1.1 years from placing the product on the market.

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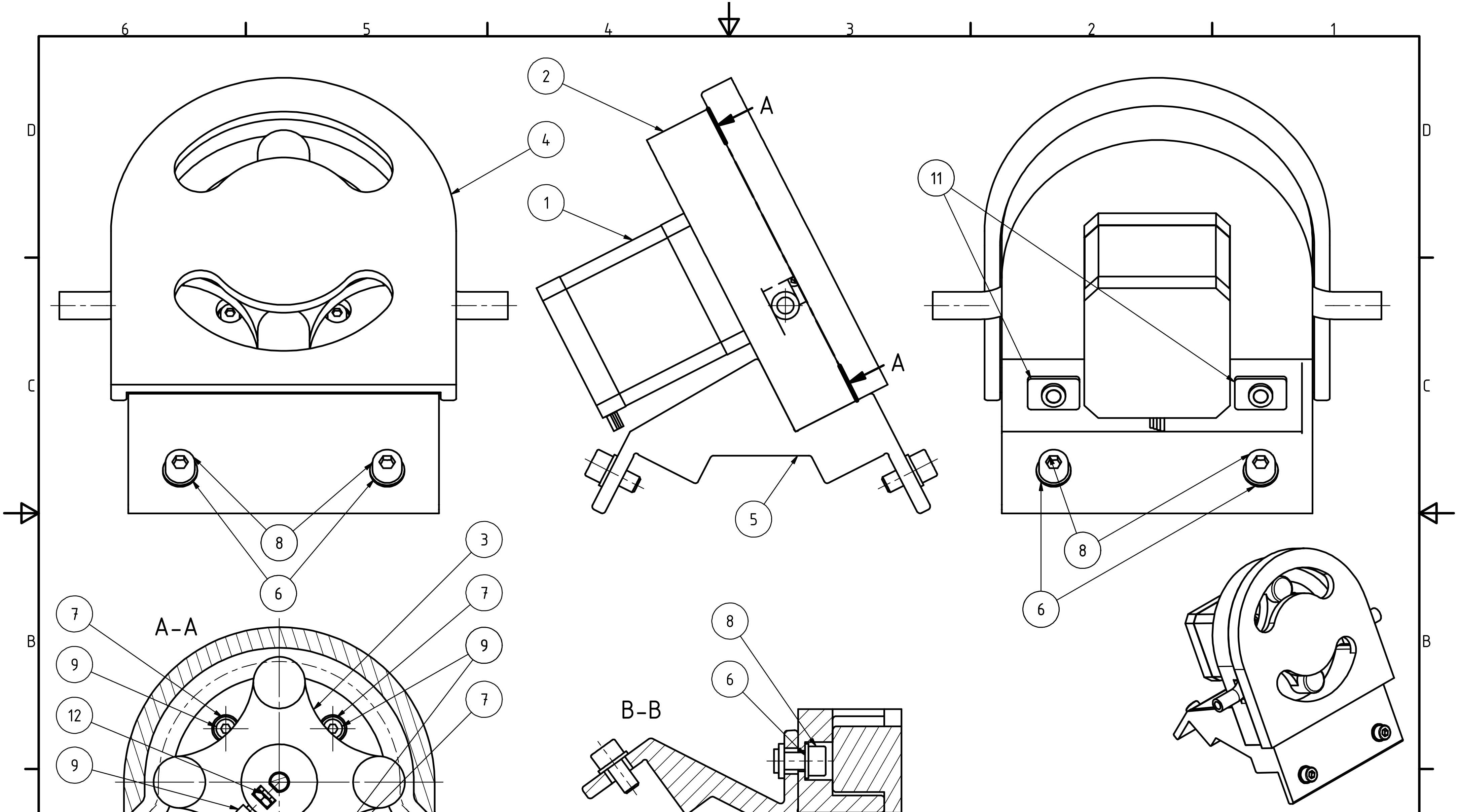

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Max. roughness	Ra=6,3				

	Date	Name
Drawn	2.6.2015	Belohlav
Checked		
Norm		

Title

PERISTALTIC PUMP

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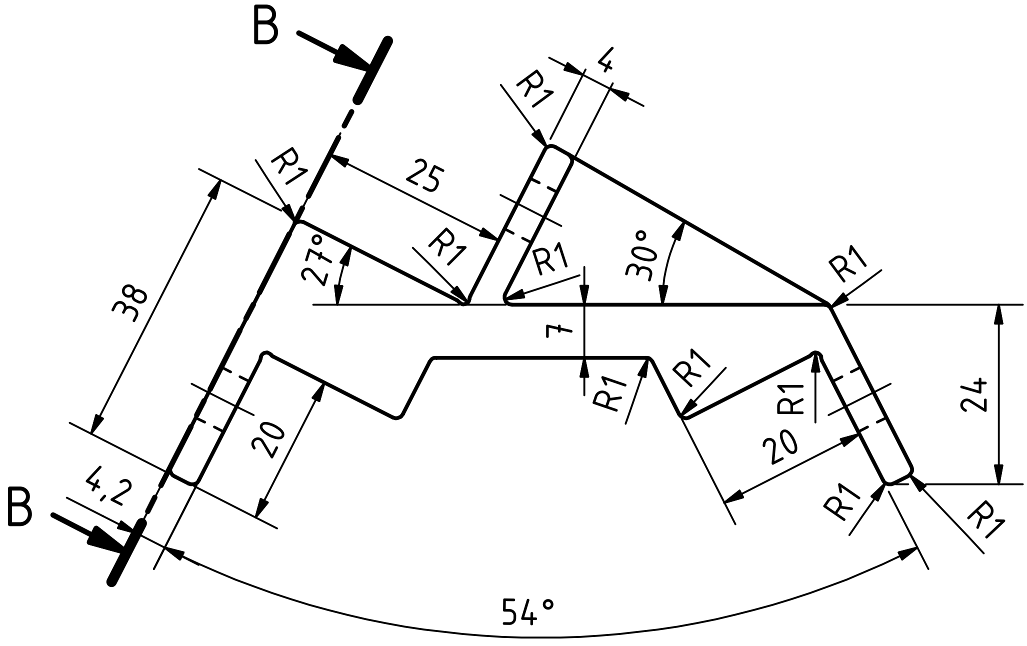

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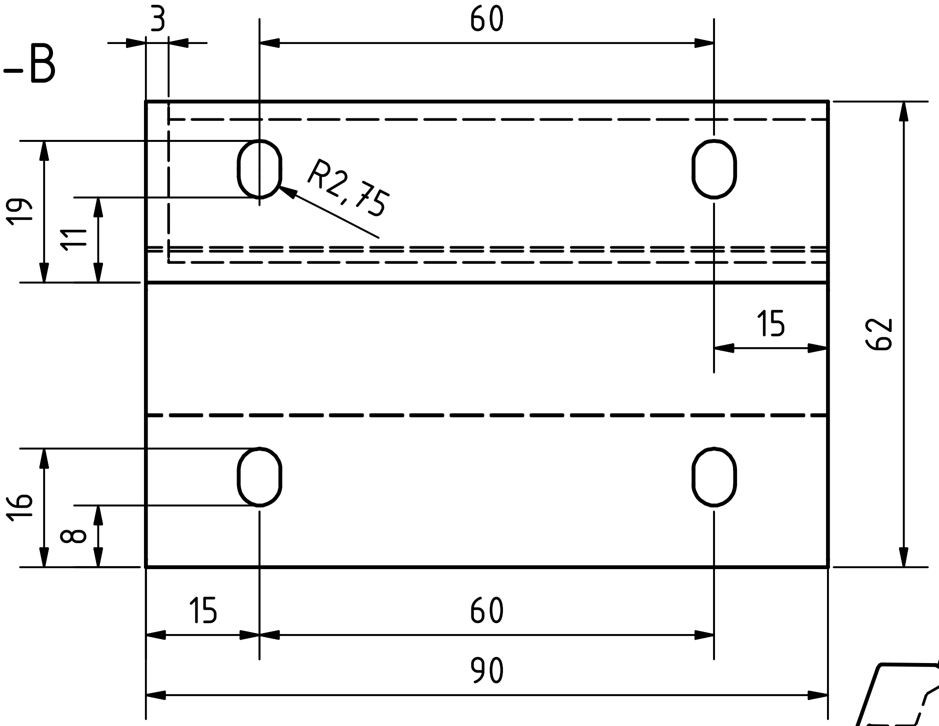

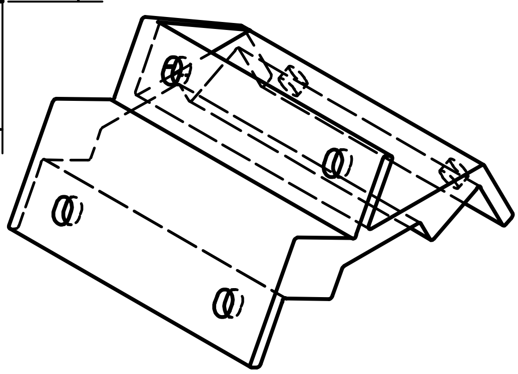

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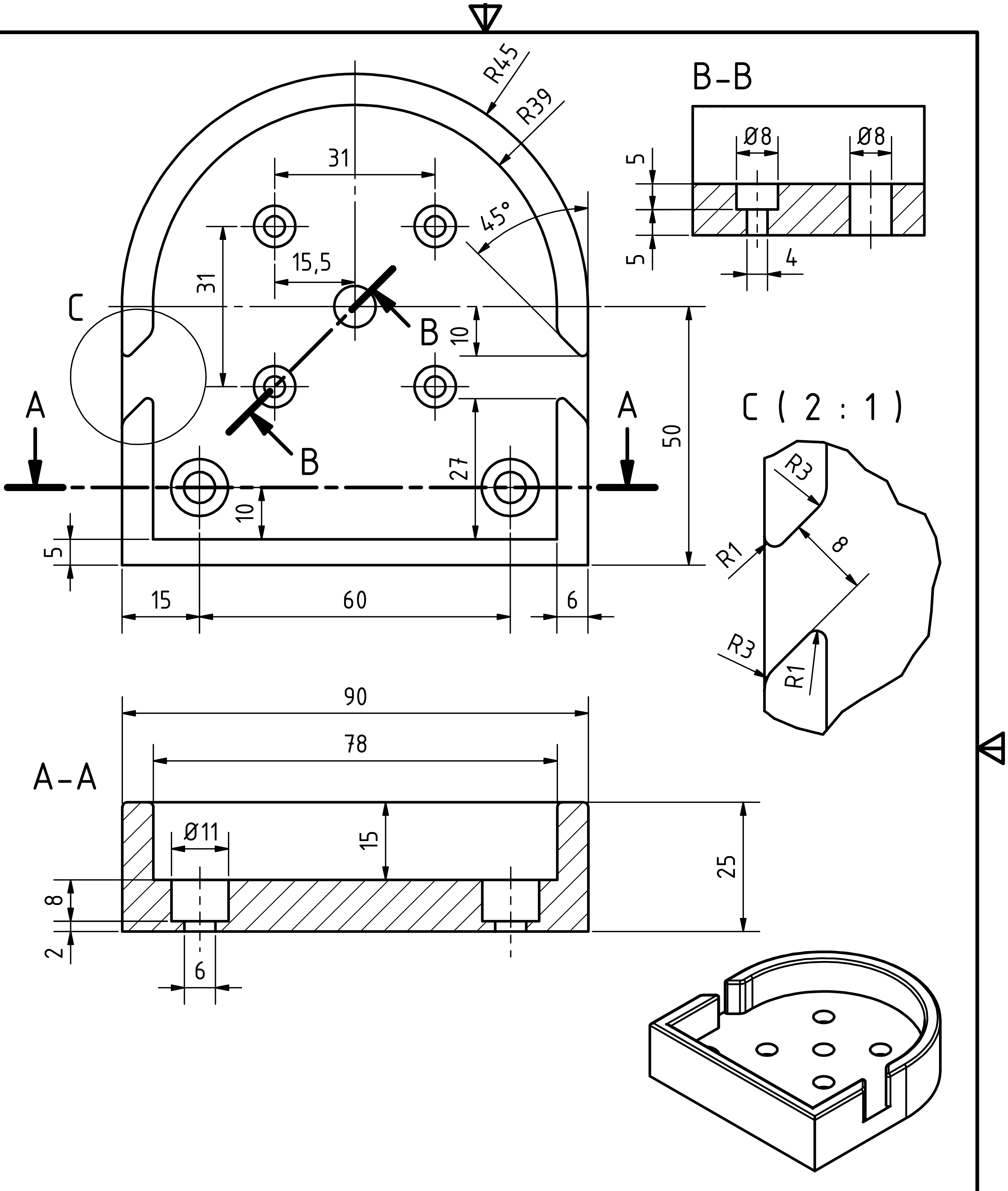

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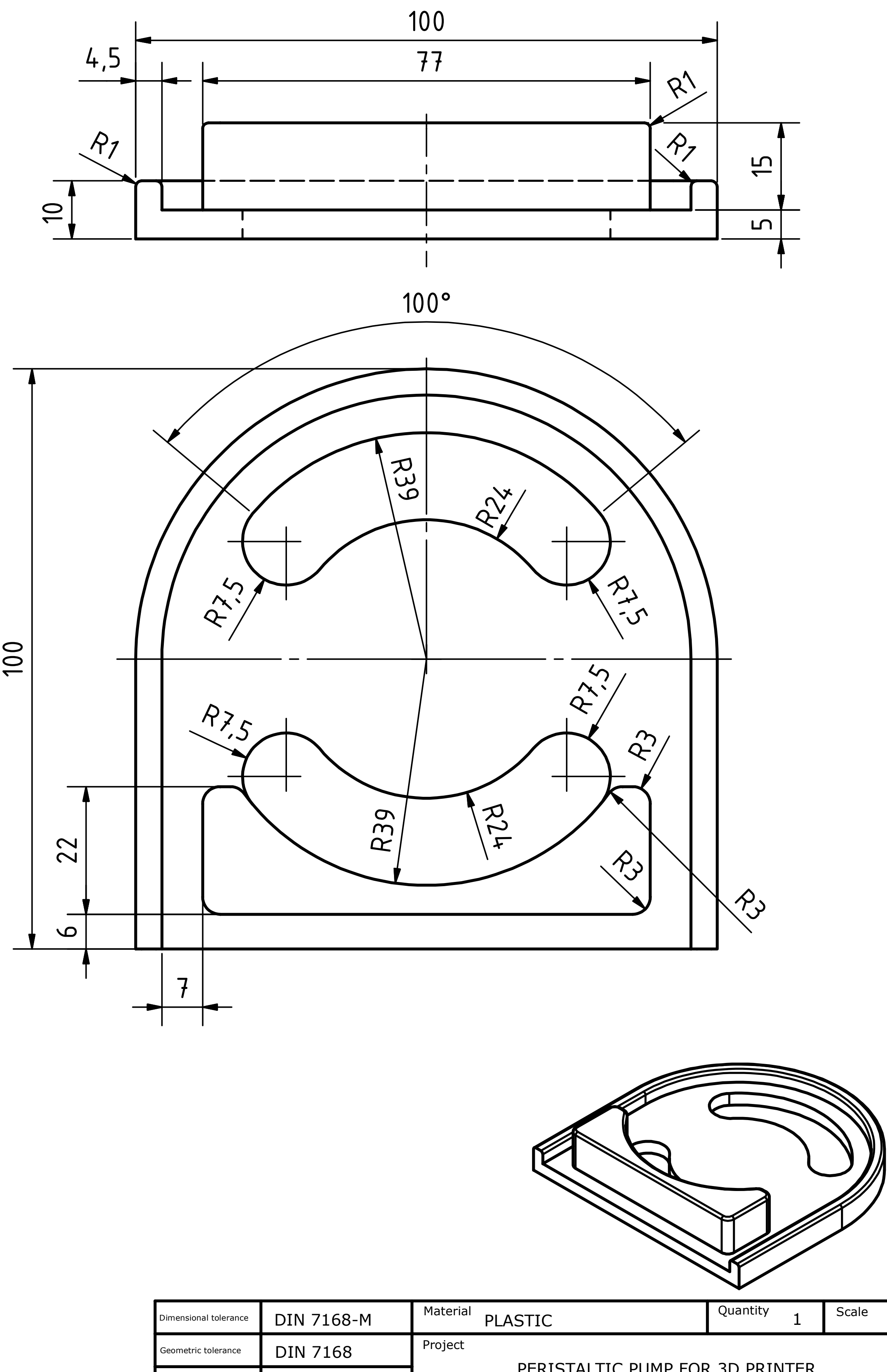

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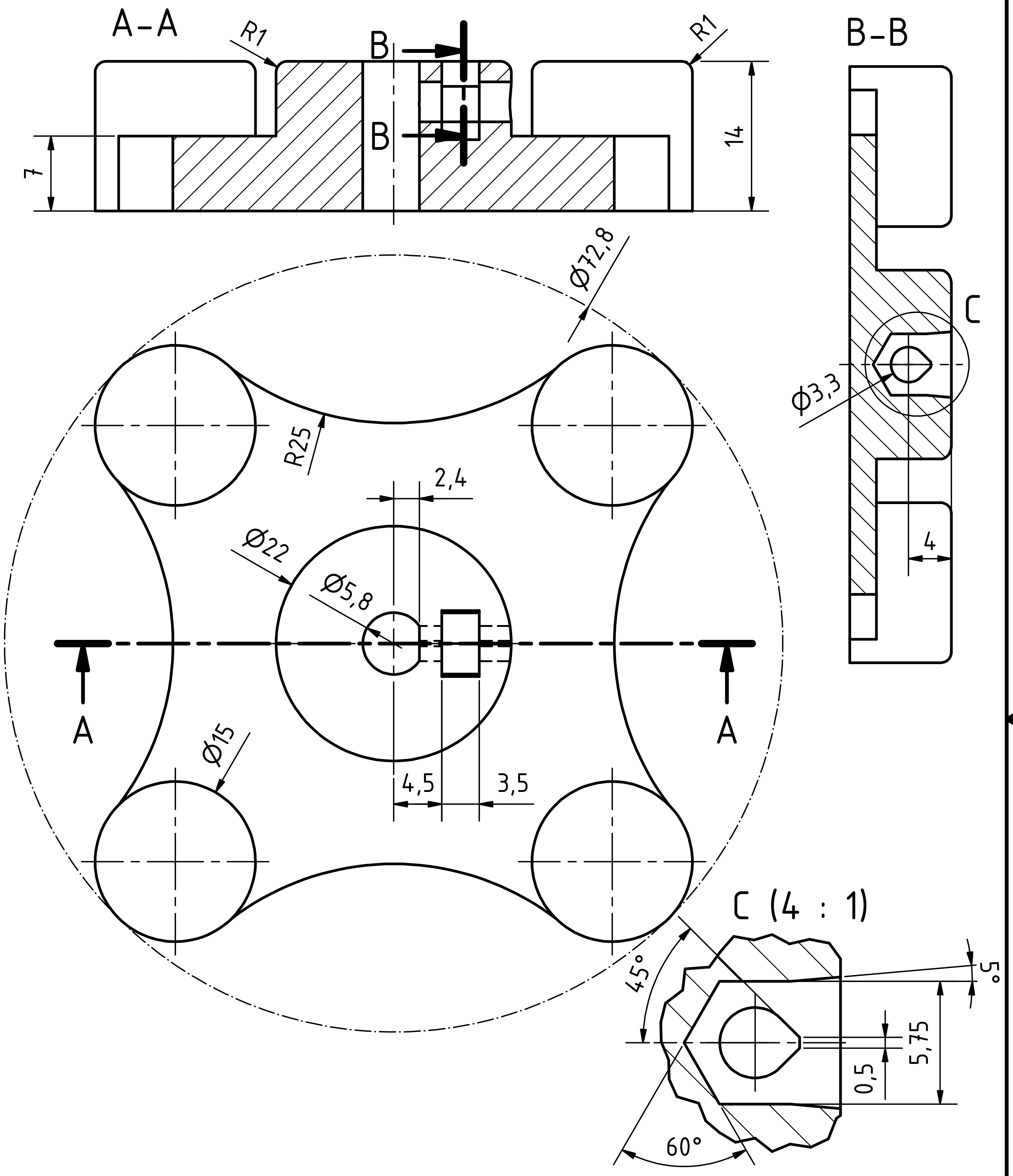
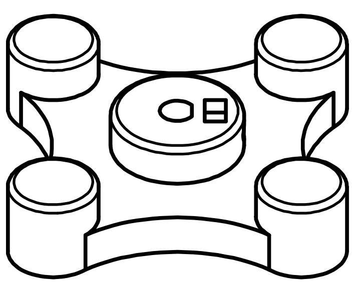
Norm					
			Drawing No. VB01-01.0003	Sheet 4/5	Size A4





Dimensional tolerance	DIN 7168-M		Material PLASTIC		Quantity 1	Scale 2:1
Geometric tolerance	DIN 7168		Project PERISTALTIC PUMP FOR 3D PRINTER			
Max. roughness	Ra=6,3					
	Date	Name	Title ROTOR			
Drawn	3.6.2015	Belohlav				
Checked						
Norm						
			Drawing No. VB01-01.0004		Sheet 5/5	Size A4